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AN OPEN LOOP MISSILE EVASION

ALGORITHM FOR FIGHTERS

THESIS

IT/GA/AA/83D-7

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THESIS

Presented to the Faculty of the School of Engineering

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Notation

PN	Proportional Navigation
TGO	Time-to-go
η	Relative Azimuth
ϵ	Relative Elevation
PP	Pure Pursuit Navigation
LOS	Line-of-sight
$\bar{r}_t$	Target Position Vector
$\bar{r}_m$	Missile Position Vector
$\bar{R}$	Relative Position Vector of Missile with respect to Target
$\hat{X},\hat{Y},\hat{Z}$	Inertial Reference Frame
$\hat{i}_t,\hat{i}_p,\hat{i}_y$	Aircraft Reference Frame
a_n	Normal Acceleration
λ	Proportionality Constant
V_m	Missile Speed
$\dot{\theta}$	Rate of Change of Line-of-Sight
M	Missile Miss Distance at any Instant
R_o	Initial Relative Range
$\dot{\theta}_o$	Initial Line-of-Sight Rate
V_c	Closure Velocity
T	Time-to-go until impact
T_o	Initial Time-to-go until impact
M_o	Initial Missile Miss Distance
R	Relative Range Magnitude at any instant
a_t	Target Acceleration

t	Time since start time
$\overline{LOS}$	Line-of-Sight Vector
$\overline{V}_t$	Target Velocity Vector
$\hat{u}_n$	Unit Normal Vector To Intercept Plane
C_{do}	Coefficient of Drag
$C_{n\alpha}$	Coefficient of Normal Force
$C_{m\delta}$	Moment Coefficient for Fin Deflection
α	Angle of Attack
δ	Fin Deflection Angle
ΔC_d	Additional Coefficient of Drag during Coast Phase
U	Non-Dimensional Target Jinking Frequency
ω_t	Target Jinking Frequency
τ_1, τ_2	Second Order Dynamics Time Constants
τ	Overall Dynamic Time Constant
ϕ	Angle Between LOS Vector and Target Acceleration Vector
$\hat{i}_v, \hat{i}_a, \hat{i}_d$	First Intermediate Unit Vector Frame
β	Rotation Angle about $\hat{z}$
γ	Rotation Angle about $\hat{i}_a$
ψ_b	Bank Angle
$\hat{i}_v, \hat{i}_e, \hat{i}_u$	Second Intermediate Unit Vector Frame
$\hat{i}'_e, \hat{i}'_u$	$\hat{i}_e$ and $\hat{i}_u$ Unit Vectors Rotated 180 Degrees about $\hat{i}_v$

Abstract

Proportional navigation (PN) is a guidance law used on many missiles today. Closed loop missile evasion maneuvers for fighters flying against proportional navigation missiles have been investigated, but they all require that the fighter have relative state information that is currently unavailable. An open loop missile evasion algorithm is needed today to allow pilots to best maneuver their aircraft against PN guided missiles to improve the chances of survival.

A preliminary investigation of fighter maneuvers revealed the strengths and weakness of particular maneuvers. Maximum g turns and barrel rolls were expected to show little increase in miss distance over a non-maneuvering target. A switching/jinking maneuver proved a good maneuver. A switching/jinking maneuver coupled with a last second bank reversal was thought to be the best evasive maneuver.

The computer simulation TACTICS IV was used to simulate fighter/missile engagements. From those simulations the miss distance was calculated and used to determine the best fighter maneuver. As expected maximum g turns in any direction and barrel rolls proved to be the worst maneuvers.

A rapid jinking maneuver that times the last reversal to occur with about one second until impact and is done in a plane perpendicular to the line-of-sight vector showed the largest increase in miss distance.

The open loop evasion algorithm for a PN missile is simple and centers around the missile being seen by the pilot. If a launch is detected but the missile is not in view, the pilot should jink as quickly as possible and in any direction. If the pilot sees the missile he should jink in a plane perpendicular to the line-of-sight vector and time the last switch to occur about one second before impact. If the missile is already one second from impact when first seen a maximum g turn perpendicular to the line-of-sight vector should be done immediately.

AN OPEN LOOP MISSILE EVASION ALGORITHM FOR FIGHTERS

I Introduction

As missiles become more accurate, better aircraft maneuvering is needed to avoid destruction. Electronic countermeasures alone generally cannot assure survival. Therefore, the pilot must know the best way to maneuver his aircraft to minimize the effects of the missile.

Need for Updated Tactics

If U.S. pilots were to go to war tomorrow, they would do so with missile evasion tactics that are at least fifteen years old. Fighter tactics for evading an attacking missile have not changed significantly since the latter part of the Vietnam War. Those tactics were to counter missiles with 1950 technology and a pure pursuit guidance law. Missiles our fighter pilots might expect to encounter today are far more advanced. Using late 1970 technology, missiles today have higher structural g' limits, quicker response times, more lethal warheads, faster speeds, quicker acceleration, and more reliable electronics. They are also smaller and more difficult for the pilot to see. Proportional navigation (PN) is the guidance law primarily used in air-to-air or surface-to-air missiles today. Missile evasion tactics must keep up with technology advancements if we are to fight effectively.

Besner (Ref 1), Borg (Ref 2), Carpenter (Ref 5), Hudson (Ref 9), Shinar (Refs 1;11) and Shumaker (Ref 12) examined closed loop missile evasion maneuvers for existing and future missiles. However, each of these closed loop evasion maneuvers assumes the pilot has near perfect information on missile position relative to his own position. A key part of these evasion schemes is the pilot's knowledge of the relative range and closure rate of the missile with respect to his aircraft. Today that information is only available as a rough guess made by the pilot or navigator. If the missile is not in the boost phase (ie, smoke, and flame coming out of the exhaust) then it is unlikely that it will be seen in time to permit an estimate of relative range and range rate. Add to that the fact that many missile launches will be from behind the aircraft where crewmembers have very limited visability with which to make the needed estimates. Advanced radar/infrared systems are being developed and tested which will be able to provide this state information, but they are years away from operational use. Hence, the need for a study to explore open loop missile evasion maneuvers which can be used now.

Target Assumptions

A pilot in a present day fighter has only his eyes and experience to use in sighting and avoiding a guided missile. Assuming the pilot of the aircraft under attack can see the missile, the best he can do is to estimate the relative range, azimuth and elevation of the missile with respect to his air-

craft. He may be able to estimate the relative elevation and azimuth to within 10 degrees; estimating range will not be as easy. Fighter pilots seldom train in estimating the range of missile/rockets fired at them; consequently range estimitations may be in error by as much as 2500 feet. If an attempt at estimating relative range is bad any attempt to estimate relative velocity is no better.

The best that the pilot can usually do is to estimate a time-to-go (TGO) until missile intercept in the last few seconds based on the apparent closure rate. Therefore, the only known information the pilot will have about the missile is estimates of relative range, azimuth (η), elevation (ϵ), and time-to-go until intercept. (Fig 1.1)

Since the target, generally has no accurate data on the relative state of the missile it is difficult to develop any closed loop evasion maneuver. The pilot will know accurately the position, heading, airspeed, and altitude of his aircraft; however, the lack of timely, reliable data on the missile prevents one from building a system that can process this data and compute the acceleration vector needed to avoid collision. An open loop evasion maneuver is needed so that given the available data on the missile (relative range, elevation and azimuth), the pilot can execute a specified maneuver that will result in the largest missile miss distance. In order to develop an open loop evasive maneuver the characteristics of the attacking missile must be defined.

<u>Missile Definition</u>

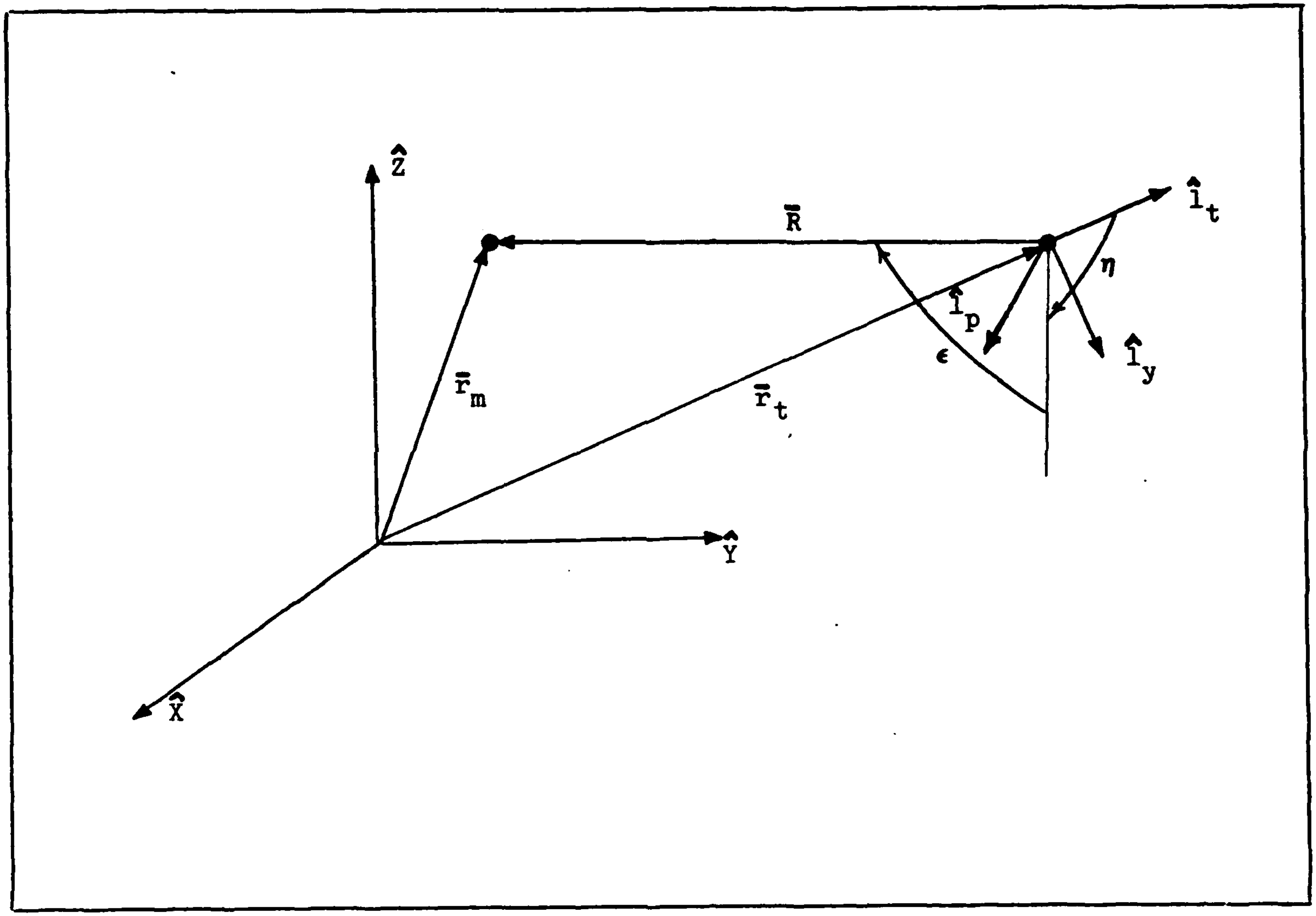


FIGURE 1,1 Relative Range, Azimuth and Elevation

The guided missile that is to be used in this study uses proportional navigation for its guidance law and performs as well or better than any currently operational missile. Proportional navigation is the type of guidance law used on most operational missiles and likely will be used in the near future; proportional navigation will be discussed later. The missile parameters used are presented in chapter III.

These parameters represent a small, highly maneuverable missile. The missile used in the computer simulation is assumed to have reached its peak velocity when the simulation begins and is in the coast phase of flight. Also, the target will fly a straight and level flight path until the missile has had a chance to establish a line-of-sight rate that is very small and the missile is flying with approximately 1 g. The seeker head with a gimbal limits of ± 90 degrees and a gimbal rate limit of 60 deg/sec meet or exceed present day missile capabilities. Only an electronically steered radar seeker could exceed these limits and that technology is not yet available in small (less than 12 in diameter) missiles.

Proportional Navigation

In the classical sense a proportional navigation course is a path in which the rate of change of missile heading is directly proportional to the rate of rotation of the line-of-sight (LOS) from the missile to the target. This results in the missile attempting to fly a course so that the line-of-sight does not rotate, hence, a constant bearing course. Forces created by missile fin deflections

result in an acceleration normal to the missile longitudinal centerline and produce the desired missile heading changes. In the classical sense this normal acceleration is expressed by Equation 1.1 (Refs 3:2-177; 8:43; 10:79)

$$a_n = \lambda V_m \dot{\theta} \tag{1.1}$$

where a_n is the normal acceleration

λ is a proportionality constant

V_m is the magnitude of the missile velocity

$\dot{\theta}$ is the rate of change of the line-of-sight

There are several variations to proportional navigation. One variation assumes the missile velocity is constant for the length of the engagement. Another uses the closure velocity (V_c) instead of the actual missile velocity. In classical proportional navigation λ , the proportionality constant, is a fixed value; in some more recent proportional navigation schemes λ is permitted to change as a function of range rate. Values for λ usually range between three and six. As λ increases the normal acceleration becomes greater for a given λ, thus the missile responds more quickly. A constant $\lambda = 4.0$ along with the missile velocity is used for the proportional navigation guidance law for the attacking missile in this study. (Refs 3:2-172; 10:79)

Proportional navigation guidance is more widely used than pure pursuit currently for several reasons. Pure pursuit

(PP) a popular guidance scheme in earlier guided missiles, creates normal accelerations so that the missiles velocity vector is always aligned with the line-of-sight. Using pure pursuit, the missile experiences maximum commanded g's in the final phase of intercept as it turns into a tail chase. (Fig 1.2). For this reason a pure pursuit guided missile is very susceptible to being defeated by a hard turn into the missile which forces the missile to its maximum structural limits. (Ref 3:2-160) Proportional navigation (PN), as it turns out, is the optimum guidance law with respect to total expended control energy for a non-maneuvering target. A PN guided missile experiences its maximum commanded acceleration early in the engagement in order to establish a lead angle for the intercept. (Fig 1.3) In the final phase of a PN missile intercept the missile is using nominal g loading and a hard break turn into the missile does not have the same effect as with the PP missile. A PN missile allows flexibility in that it can be made to be more or less responsive by simply increasing or decreasing the proportionality constant, λ between the values of two to six. For valves of λ above six the missile becomes excessively erratic and overly sensitive to noise in the seeker in the final seconds. The missile becomes unresponsive in the final seconds of intercept if λ has a value less than 2. Proportional navigation is an efficient guidance law for a target with constant velocity or turning rate. (Refs 3:2-167; 10:79)

Fighter pilots have been using proportional navigation

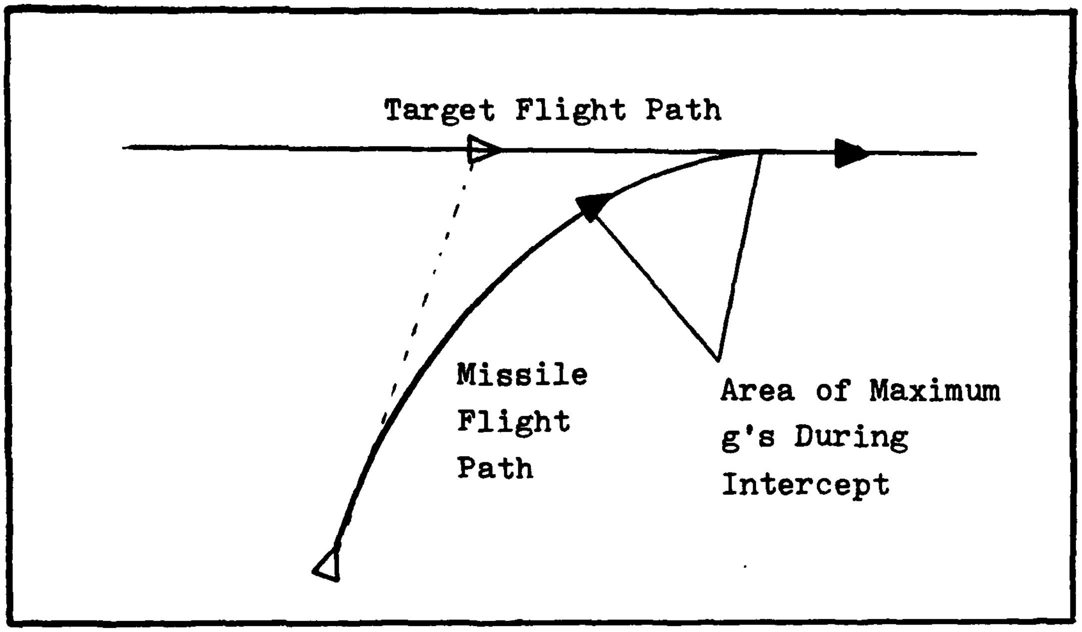


FIGURE 1.2 Pure Pursuit Intercept

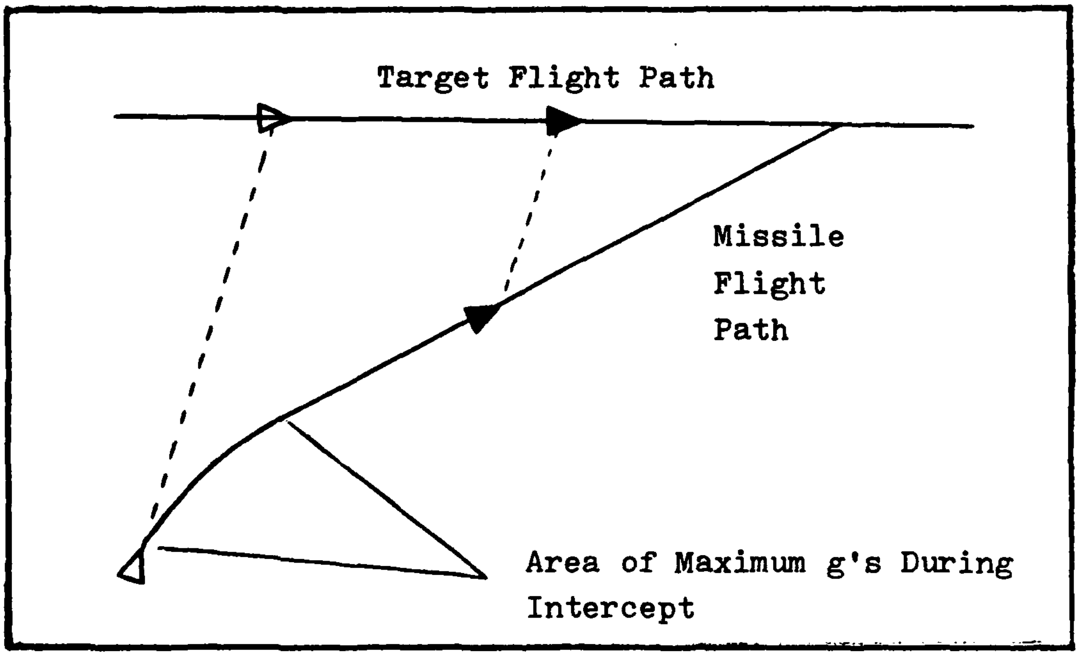


FIGURE 1.3 Proportional Navigation Intercept

for years without knowing it. When making a turning rejoin the lead aircraft turns in a constant bank, (constant turning rate) turn. The wingman initially pulls a few g's to establish a lead angle, then releases back pressure to about 1 g. From that point on he tries to keep his line-of-sight stationary so that the lead aircraft appears to stay in the same spot on the windscreen. Without changing this geometry the wingman would eventually hit the lead aircraft; however, he transitions in the last few hundred feet to other visual references and maneuvers into a fingertip position. Wingmen thus use proportional navigation as the intercept guidance law for a turning rejoin.

Objective

The objective of this thesis is to provide a simple algorithm or rule of thumb for a pilot to use when under missile attack. Several different maneuvers may be proposed with a particular maneuver suggested for given values of missile relative range, azimuth, elevation, and time-to-go.

Approach

A three phase approach was used to develop the missile evasion algorithm. In the first phase target maneuvers were examined in light of the missile guidance law and physical parameters. These maneuvers were then tested on the computer simulation TACTICS IV to establish miss distance data as phase two. Using this miss distance data, maneuvers that produced largest miss distance were selected for the missile evasion algorithm.

II Problem Approach And Missile Evasion Algorithm

The first step in an attempt to defeat an enemy must be an analysis of his weaknesses. The enemy in this situation is a missile using a proportional navigation guidance law. First, the proportional navigation guidance law is examined to identfy target maneuvers that might succeed in increasing the miss distance. Next, the missile will be examined for limitations that might be exploited through aggressive maneuvering. Through this approach a starting point will be established for choosing target maneuvers to be checked with the computer simulation.

Effects of Target Maneuvering on the Guidance Law

As a guidance scheme, proportional navigation attempts to steer the missile towards a collision with the target by calculating an output steering command from given input information. The output commanded is an acceleration normal to the missile's longitudinal axis. The main input information comes from the missile seeker head and, in proportional navigation is the line-of-sight rate measured from seeker head motion. The function relating the input and output is as follows

$$a_n = \lambda V_m \dot{\theta} \qquad (2.1)$$

This is the equation for classical proportional navigation used in this problem. (Refs 3:2-177; 8:43; 10:79) The output, a_n, is the normal acceleration and this is always bounded by the longitudinal structural limits. The magnitude of the missile velocity, V_m, is an input that behaves like a scale parameter in that as the missile slows down the closure rate typically slows down, thus, the missile does not need to turn as quickly. Also, as the missile slows, fewer turning g's can be produced. The main input is the line-of-sight rate, $\dot{\theta}$ of the missile to target vector. It is this parameter that target maneuvering can affect the most. Target maneuvers that will create a large $\dot{\theta}$ values will in turn cause large values of commanded acceleration. The proportionality constant, λ , is the third input and it is the input that target maneuvering generally does not change. Even so, this proportionality constant might be exploited by target maneuvering as will be seen later. For now, the missile speed and line-of-sight rate of the target with respect to the missile are two guidance law inputs that can be affected by target maneuvering.

The missile normal acceleration, a_n, should be made as large as possible as often as possible to help increase miss distance. By keeping a_n large the miss distance can be increased in two ways. For a constant-velocity target, the projected miss distance at any time is defined by Equation 2.2 (Refs 3:2-172; 10:79)

$$M = \frac{R_o^2 \dot{\theta}_o}{V_c} \left(\frac{T}{T_o} \right)^{\lambda} = M_o \left(\frac{T}{T_o} \right)^{\lambda} \tag{2.2}$$

where R_o is the initial relative range

$\dot{\theta}$ is the initial line-of-sight rate

V_c is the closure velocity

T is the time-to-go ranging from T_o to 0

T_o is the initial time-to-go equal to R_o/V_c

M_o is the initial miss distance at $T = T_o$

As seen from this equation the expected miss distance during an engagement with a non-maneuvering target is primarily dependant upon M_o. Also, the initial miss distance, M_o, is dependant upon the initial line-of-sight rate, $\dot{\theta}$. However, assume that R_o is defined as the relative range, R, and $\dot{\theta}$ is the $\dot{\theta}$ value at the instant when the target begins a maneuver. Thus the miss distance, M, at that instant is

$$M = \frac{R^2 \dot{\theta}}{V_c} \qquad (2.3)$$

The miss distance then begins to decrease if the target stops maneuvering. Thus the target should continue to maneuver so that at any given R the miss distance at that instant is made large by decreasing V_c, increasing $\dot{\theta}$ or both. Since the missile in this problem is assumed to have burned out and be in the coast phase it is gradually slowing down due to drag. One way to decrease the closure velocity is to slow the missile down faster. The target can cause this to happen by maneuvering so that the missile must create high lateral g's, hence, higher angles of attack and larger values of

drag. Another way to decrease the closure velocity is for the target to fly away from the missile. Target maneuvering to maintain $\dot{\theta}$ large at a given R will also result in a larger miss distance as well as a large a_n value. Thus, target maneuvering to keep $\dot{\theta}$ large results in large a_n values and a faster missile slow down giving larger miss distances.

Missile Limitations

The missile has physical limitations that can be exploited by a maneuvering target. Structural g limits, seeker head limits and time delays are parameters which are vulnerable. If $\dot{\theta}$ can be made large enough, the commanded a_n may cause the missile to exceed its structural limits thus increasing the miss distance since the missile will not be able to turn as quickly as needed. The gimbal rate limit is the maximum rate that the gimballed sensor on the seeker head can move. It is this measured gimbal rate that is used to determine $\dot{\theta}$. If maneuvering can cause $\dot{\theta}$ to exceed this gimbal rate limit then the sensor will no longer be able to keep the target in its field of view. Once this happens the missile loses the main input to its guidance law and again the miss distance will increase. If the sensor gimbal angle limit is reached the same result is acheived. Finally, there are time lags in all electro-mechanical systems causing output responses to lag the input commands. Since there is a delay between the commanded missile acceleration and actual acceleration response the target may be able to preform a last

second maneuver such that the missile response time will not allow a correction in time to assure a hit. Since the missile response is typically faster than the pilot/aircraft, any last second maneuver must be critically timed to permit the largest aircraft displacement in a time too short for the missile to respond. Also the target may be able to move in a weaving motion to take advantage of this time delay and set up some sort of resonance such that a gimbal or structural limit might be reached. Missile physical limitations indicate that target maneuvers should create large line-of-sight rates, possibly induce resonant instability or cause sudden last second physical displacements to increase the miss distance.

Target Maneuvers Examined

The target maneuvers to be examined were chosen to exploit the guidance law parameters and physical missile limitations. They also must be physically possible for the pilot and fighter type aircraft. The maneuvers tested were maximum g turns into and away from the missile, barrel rolls, jinking, maximum g turns with a last second reversal and jinking with a last ditch reversal. These maneuvers represent practically all of the maneuvers that a fighter can accomplish and most have some potential for creating the desired large line-of-sight rates and resonance.

Maximum g turns towards or away from the line-of-sight vector from the target to missile have potential for creating large $\dot{\theta}$ values. However, it is very difficult to

create values of $\dot{\theta}$ large enough to exceed the gimbal rate or reach maximum structural g limits. Consider the example where a missile has tracked the target such that $\dot{\theta} = 0$, the missile has a constant bearing course towards a perfect intercept. Suddenly the target turns into the missile in the same plane formed by the line-of-sight vector and the missile velocity vector, as shown in Fig 2.1. Now let the target acceleration vector be perpendicular to the line-of-sight vector with a magnitude of 8 g's and the closure velocity be 1500 fps. The line-of-sight rate is represented by Equation 2.4. (Ref 3:2-175)

$$\dot{\theta} = \frac{a_t}{V_c}\left[\frac{1}{\lambda - 2} - \left(\frac{1}{\lambda - 2}\right)^{(1-t/T_o)^{\lambda-2}}\right] \quad (2.4)$$

a_t = target acceleration 8 g's = 257.6 ft/sec

V_c = closure velocity 1500 ft/sec

t = time since start time

T_o = total time computed until intercept

λ = navigation constant, 4

Substituting in values for a_n, λ and V_c

$$\dot{\theta} = 0.177\left[\frac{1}{2} - \frac{1}{2}^{(1-t/T_o)^2}\right] \quad (2.5)$$

The point at which the target first starts its turn is the point of maximum range during the turn. At that time we assume t=0 and $\dot{\theta} = 0$ as expected. When the missile is just

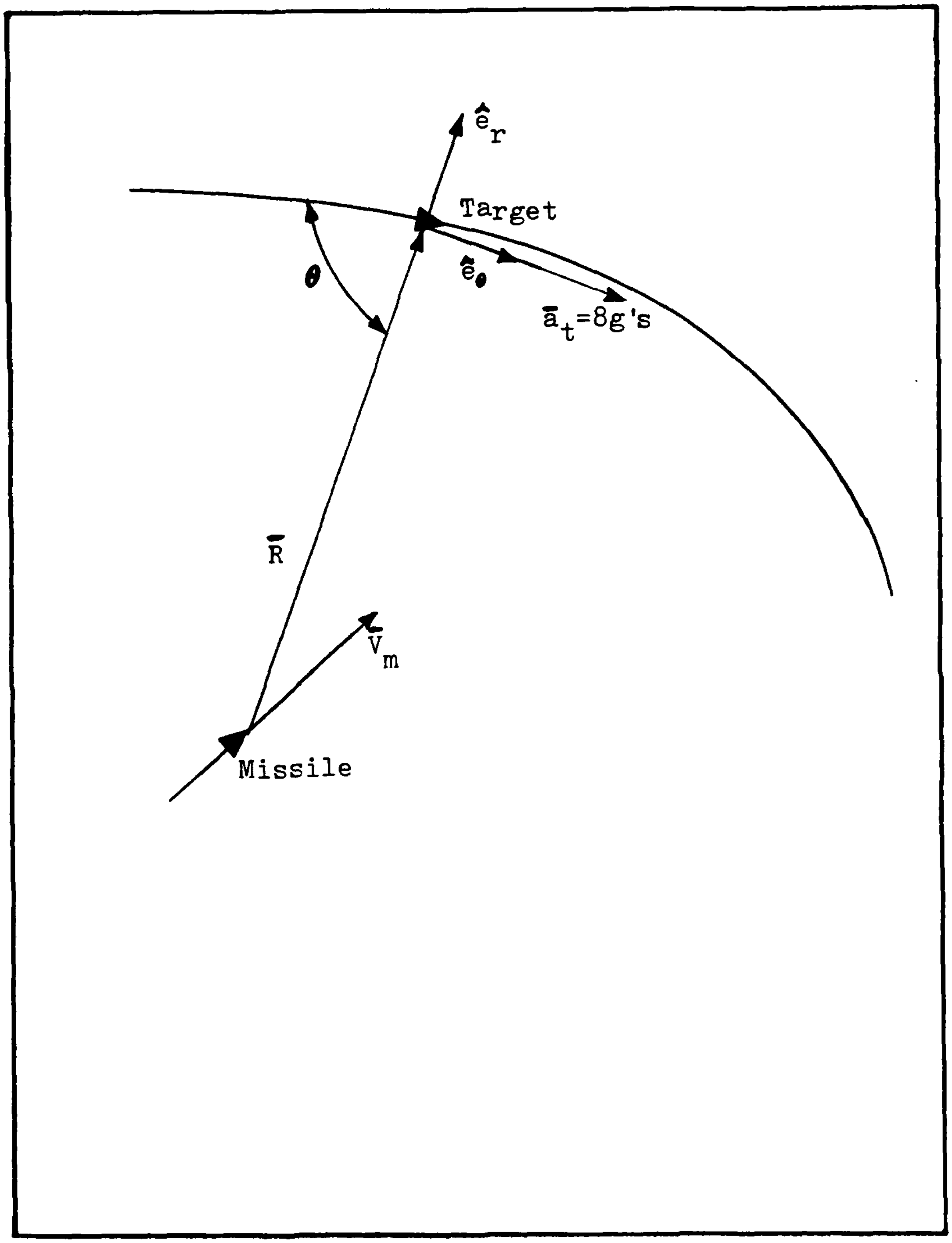


FIGURE 2.1 Maximum g Turn in the Plane of Intercept

at impact, $t = T_0$, $\dot{\theta} = 0.086$ rad/sec. A graph of $\dot{\theta}$ vs t/T_0 for this case is shown in Fig 2.2.

As can be seen a constant maximum g turn into the missile gives very small values of $\dot{\theta}$. This is expected since proportional navigation, as was mentioned earlier, works very well on constant velocity or constant turning target. Turns away from the missile or out of the plane give similar results. The main value in a maximum g turn is as a last second maneuver when the missile might not respond quickly enough due to time lag limitations. It is expected that maximum turn maneuvers for attacks made from any azimuth angle result only in a small increase in miss distances compared to a non-maneuvering target.

The barrel roll has potential for varying $\dot{\theta}$ or creating a resonance. A barrel roll of 4 g's and a roll rate of 90 deg/sec was selected for examination. It is a realistic maneuver for all three fighter aircraft with the roll rate of 90 deg/sec being a rapid roll rate. One would expect that in order to create large $\dot{\theta}$ values a rapid roll would be required. A slow barrel roll would produce a large target diplacement but as seen in the maximum g turn large displacements do not necessarily create large $\dot{\theta}$ values. The barrel roll also has potential for creating a resonance in a roll-to-turn missile. In a roll-to-turn missile the missile commands a roll before the fins are deflected to align the fins perpendicular to the plane in which the command acceleration acts. If the barrel roll can induce a missile rotation

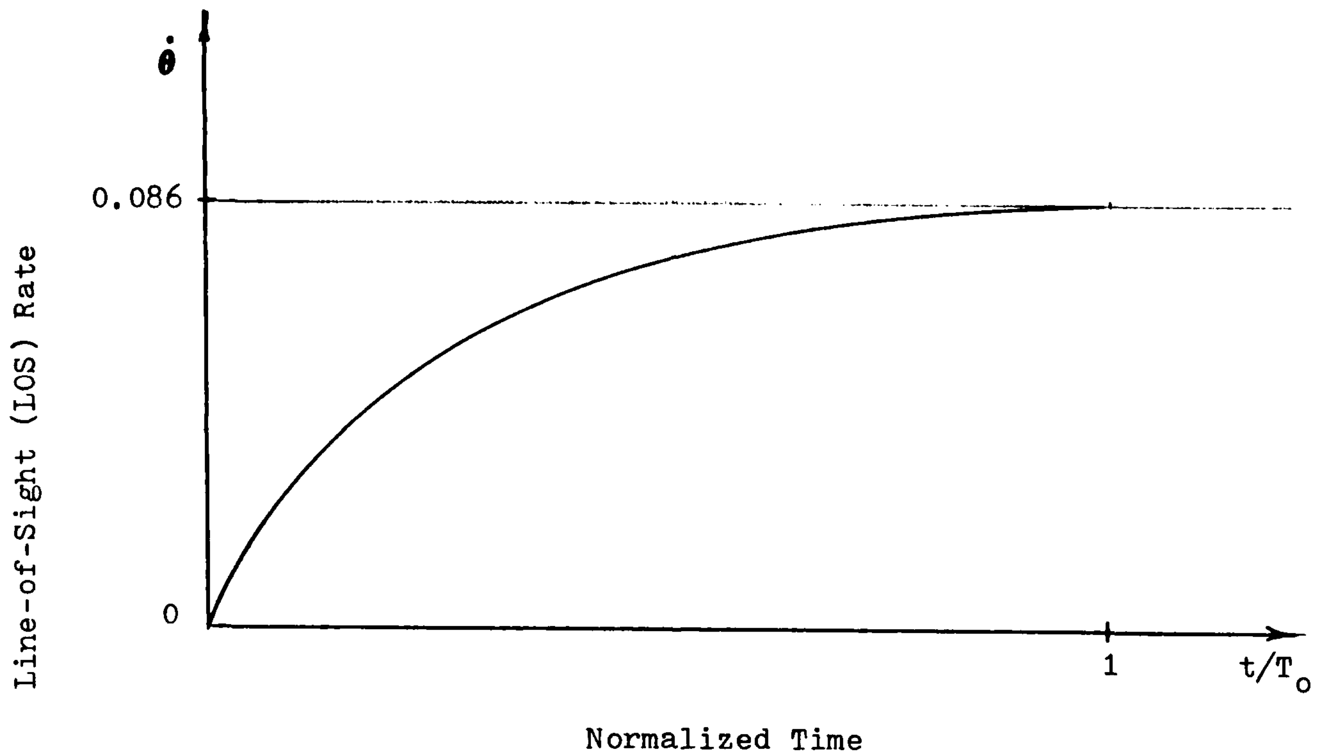


FIGURE 2.2 LOS Rate vs Normalized Time

preventing the missile from establishing that acceleration plane then it will be unable to intercept the target. However, since the missile considered is a point target without orientation it represents a skid-to-turn missile. A skid-to-turn missile does not roll to align its fins in any particular plane. It computes fin deflections for separate orthogonal pairs of fins thus creating the desired normal acceleration. Skid-to-turn missiles are becoming more popular and one can expect to more probably encounter them in the future. Since the missile used in this analysis is a skid-to-turn type the barrel roll should not be an effective target maneuver.

The jinking maneuver also has the ability to vary the line-of-sight rate, but its strength is its ability to create a resonance. The jink examined is a planar, sinusoidal switching maneuver with a constant period. The plane and the period of the maneuver can both be specified by the modified version of TACTICS IV. TACTICS IV is the computer program used in this study and is discussed in the next chapter. Since a missile with proportional navigation attempts to lead the target, a switching maneuver should radically disrupt the missiles lead angle forcing large changes in missile acceleration. There are two advantages to this. One advantage is that large acceleration changes will result in increased drag and consequently a slower missile at interception. As seen earlier a lower closure velocity results in a larger miss distance. The other advantage is that if the target can switch fast enough and at the right frequency perhaps a resonance can be set up in the missile. A resonance would

tend to cause the missile seeker head to break lock and thereby deny the missile guidance system needed input information. The jink maneuver may hold some hope of a definite increase in miss distance.

The last set of maneuvers is the maximum g turn and the jink with the last second reversal. The basic maneuver will have the same effect on the missile. The difference is the final last ditch reversal to try to avoid a collision. The last second movement can hopefully take advantage of the missiles time lag to create a larger miss distance. The main problem with this maneuver is that the pilot must be able to see the missile in order to estimate a time-to-go until impact when the reversal will be made. This last second reversal could help make the miss distance of both basic maneuvers even larger.

Computer Simulation

The maneuvers previously mentioned were all tested against a missile using the TACTIC IV simulation. (Ref 8) For each simulation the missile was assumed to have just burned out at a range of 18,000 ft from the target with a speed of Mach 2.5. It was also assumed that at burnout the missile had acheived a near perfect lead angle for the constant velocity target such that the missile was flying with approximately one g and a line-of-sight rate, $\dot{\theta}$, of approximately zero. In each case the missile was located in inertial space at the coordinates X=0, Y=0, and Z= 6,000 ft where X and Y represent an arbitrary ground reference frame and Z repre-

sents altitude. Initially the target was flying straight and level at the corner velocity. This situation is realistic for a fighter flying to or from some objective. Under most combat conditions a fighter will try to fly near corner velocity at all times. Corner velocity is defined as the minimum speed at which the maximum structural g's can be attained. It is that speed at which an aircraft has the best turn rate. At the start of each simulation the point target is located at the inertial coordinates X = 0, Y = 18,000 ft and Z = 6,000 ft. (Fig 2.3) The target's velocity vector is varied such that the initial azimuth ranges from 0 to 180 degrees in 30 deg increments. Initial elevation angles of zero and 45 degrees were teseted. For an explanation of the azimuth and elevation angles see Appendix C. These are the initial conditions for each missile/target engagement.

The point at which target maneuvering began was varied by using relative range as the initiation parameter. After starting the simulation the target maintains its straight and level flight path until a specified relative range is reached. This is to simulate the missile flying unobserved until achieving a particular relative range from the target. When that range is reached the target initiates the specified maneuver. In the trials where the target performs a last ditch reversal that part of the maneuver is initated on time-to-go until impact. For each maneuver tested the range-to-go was varied. The ranges tested were 15,000, 12,000, 9,000, 6,000, and 3,000 ft. (Fig 2.4). The time-to-go used to initiate the last second reversal was one second. Within a

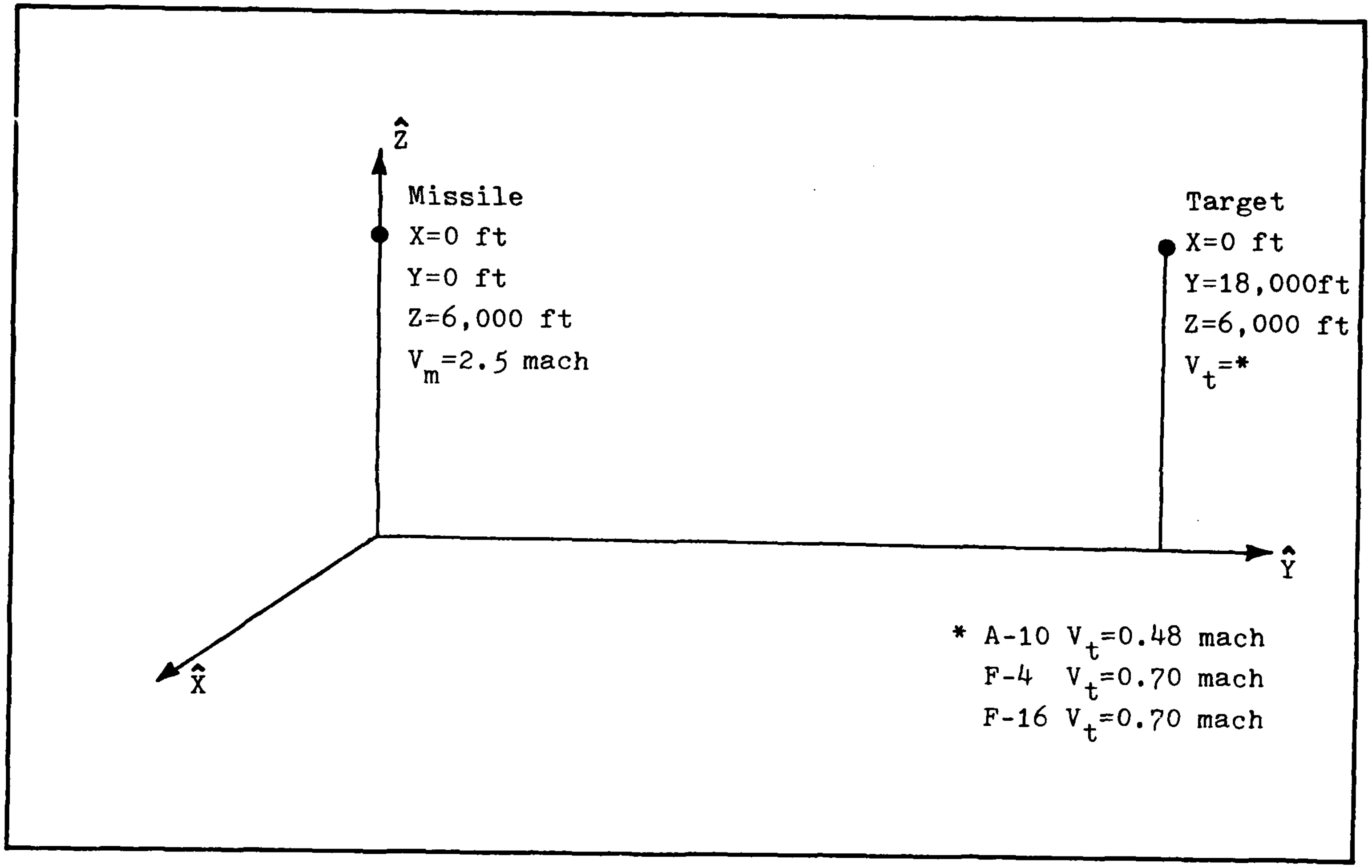


FIGURE 2.3 Initial Conditions for the Simulation

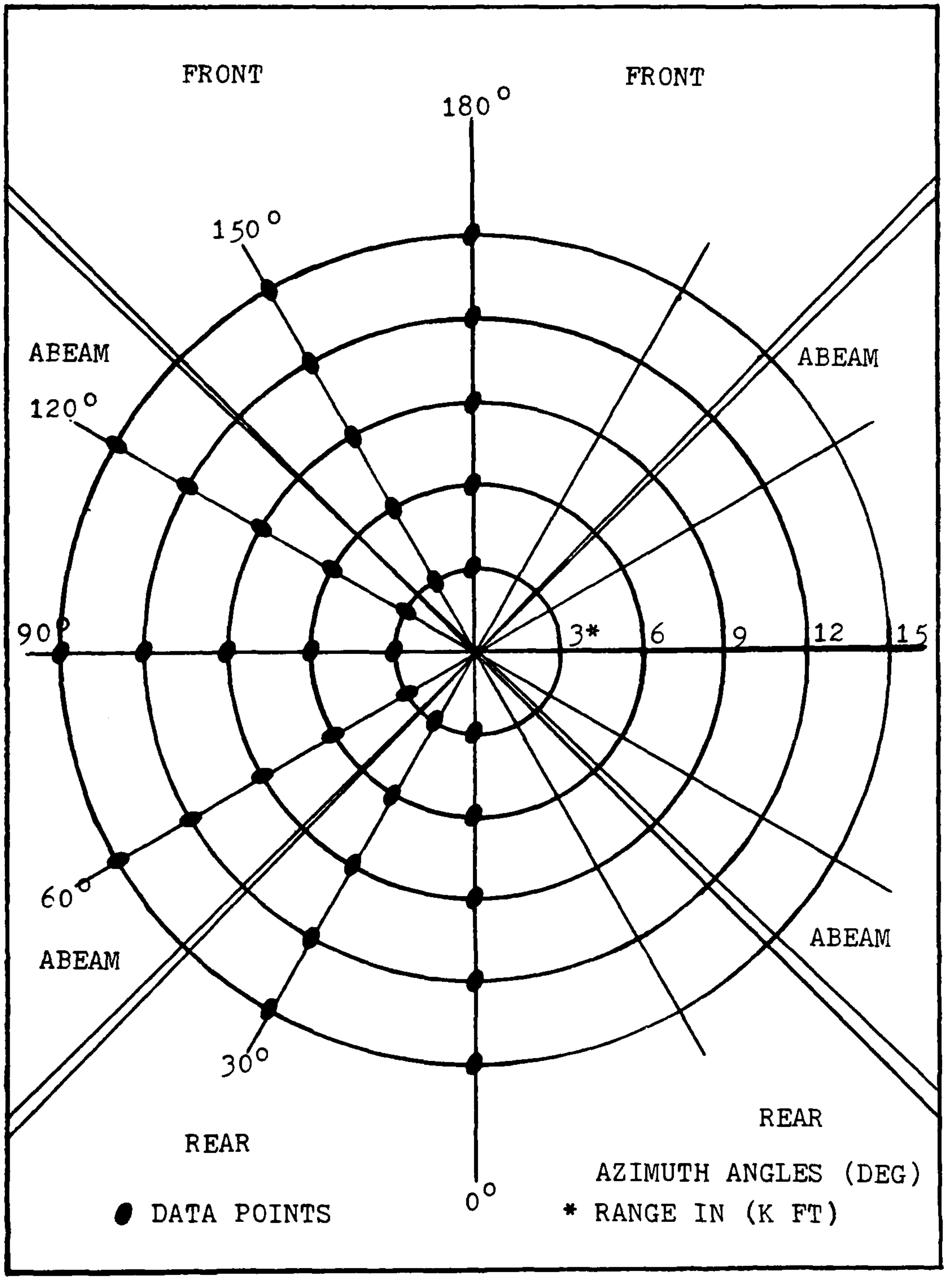


FIGURE 2.4 Data Points and Zones

range of 3,000 ft the maximum-g turn and the maximum-g turn with a last second reversal were tested at ranges 2,500, 2,000, and 1,500 ft. One second time-to-go was still used for the second reversal. In this way the target maneuvering was checked for sensitivity to relative range as an input to the missile evasion algorithm.

Three different types of fighters were tested to compare their performance in terms of miss distance. The fighters selected were an F-16, F-4, and A-10. These three were selected since they represent a broad spectrum of fighter capabilities. Each fighter was simulated by using its corner velocity at 6,000 ft altitude for a standard day and by using a maximum g limit that would approximate the maximum combat g limit. The values used to simulate each fighter are listed in Table 2.1. (Refs 13; 14; 15)

Finally, the closed loop evasion maneuver MAXACC was tested for use as a comparison to the open loop maneuvers. Miss distance is the standard for evaluation of the maneuvers. The simulation results were used to establish the miss distance for each maneuver. The maneuvers for the missile evasion algorithm were selected based on their miss distance.

Maneuver Simulation Results

Numerous simulations were made searching for the best miss distance for a given maneuver. Maximum g turns were simulated in and out of the intercept plane formed by the target velocity vector and LOS vector. Barrel rolls done at roll rates of 30, 60, and 90 deg/sec. Jinks were made with periods

ranging from 3 to 9 seconds. The jinks were also made in and out of the above mentioned intercept plane. Finally, maximum g turns and jinks were examined with a last second reversal. The reversal was made at either 180 degrees or 90 degrees to the original maneuver plane. In addition, the closed loop MAXACC maneuver was also tested.

Table 2.1 Corner Velocity and Maximum g Limit for Fighters

	Mach #	G's
A-10	0.48	5.0
F-4	0.70	6.0
F-16	0.70	8.0

The results for eight different maneuvers are listed in Table 2.2 for a brief comparison. In that table the miss distance listed for each fighter is the average miss distance for an attack made from a rear, abeam or front attack. The averages are taken for maneuvers initiated at relative ranges of 3,000, 6,000, 9,000, 12,000, and 15,000 ft. The rear, abeam and front attacks are based on relative azimuth and Fig 2.4 shows where these zones are located as well as which data points were used to establish the average miss distance for

TABLE 2.2

Comparison of Simutation Results

* Miss Distance in feet

Horizontal Maximum G Turn

	A-10	F-4	F-16
Rear	1.6	1.3	3.2
Abeam	2.3	2.8	4.4
Front	3.0	4.8	7.0

Barrel Roll

	A-10	F-4	F-16
Rear	2.3	2.2	2.2
Abeam	3.9	1.8	1.8
Front	6.9	4.8	4.8

MAXACC

	A-10	F-4	F-16
Rear	2.7	3.6	4.7
Abeam	2.6	2.7	4.2
Front	6.0	8.0	12.4

Horizontal Jink W/3.75 Second Period

	A-10	F-4	F-16
Rear	6.6	18.4	24.5
Abeam	4.5	4.3	8.8
Front	7.8	16.4	25.2

TABLE 2.2 Cont.

Comparison of Simulation Results

* Miss Distance in feet

Vertical Jink W/3.75 Second Period

	A-10	F-4	F-16
Rear	9.4	31.8	42.2
Abeam	8.4	13.0	17.5
Front	9.3	15.2	24.8

130 Deg Bank, Maximum G Turn W/ 1 Second 180 Deg Reversal

	A-10	F-4	F-16
Rear	10.2	10.1	21.8
Abeam	8.1	9.8	26.8
Front	10.1	12.5	26.8

Horizontal Jink W/3.75 Second Period and 1 Second 90 Deg Reversal

	A-10	F-4	F-16
Rear	19.7	17.4	24.9
Abeam	9.7	14.3	17.9
Front	10.0	17.1	28.1

Vertical Jink W/3.75 Second Period and 1 Second 180 Deg Reversal

	A-10	F-4	F-16
Rear	25.8	31.9	50.4
Abeam	13.5	25.2	39.9
Front	13.7	18.2	28.3

that region. For comparison the eight cases presented were made with an initial relative elevation angle of zero degrees, however, for the elevation angle of +45 degrees the results were very similiar. Results for all of the data points for these maneuvers are listed in Appendix A.

As was expected, the miss distances for a maximum g turn and the barrel roll are very small. The difference in miss distance for these two maneuvers show little increase over those values of miss distance for a non-maneuvering target shown in Table 3.3. The only real improvement over a non-maneuvering target comes from the 3,000 and 6,000 ft cases in a head-on situation. In those situations with the highest closure rates the maneuver initiation at those closer relative ranges begins to look like a last ditch move and the missile is not entirely able to correct for such last second movement. Other than in the two head-on cases, the relative range at which the maneuver was initiated appears to have no influence on the miss distance. Clearly these maneuvers do not significantly improve the miss distance.

There are four jinking maneuvers shown where two have last second reversals and two do not. Of the two that do not have a last second reversal one is jinking in the intercept plane and the other is jinking perpendicular to that plane. The most significant difference between these two maneuvers is that the abeam values for the vertical jink, perpendicular to the plane, are approximately double those same values for the in-plane jink. For the two cases with the last second reversal once again the jink done perpendicular to the inter-

cept plane gives the better average miss distance. Thus, it appears that jinking in a plane perpendicular to the intercept plane is the better maneuver. The results also show that the last second reversal dramatically increases the average miss distance. From the data shown the jinking perpendicular to the initial intercept plane with a final second reversal gives the largest miss distance.

The maximum g turn with the last second reversal shows miss distances that approximate those of the vertical jinking maneuver. The average miss distance is much better for a maximum g turn with a final second reversal than it is for a maximum g turn without the final move. A maximum g turn with a bank angle of 130 degrees is called a sliceback. Not only is this maneuver out of the intercept plane, but it also has the advantage of being able to use gravity to increase the effective g. Even so, this maneuver appears no better than the vertical jink without the reversal and worse than the vertical jink with the reversal. Although the sliceback with the last second reversal is a big improvement over any other maximum g turn, a jinking maneuver still seems to be better.

Finally, the closed loop evasion maneuver MAXACC failed to show good miss distance results. The objective of this target maneuver is to maximize the missile's normal acceleration at all times. Even though this maximum acceleration maneuver may have worked successfully in forcing the missile to fly at large values of acceleration most of the time those values of acceleration were below the maximum struct-

ural g limit, thus the missile was still able to perform normally. The only degradation in missile performance was that it slowed down faster because of the higher g requirements. From this it can be seen that a proportional navigation guided missile with perfect information is very difficult to evade by maneuvering alone. This is true even with a closed loop evasion maneuver.

Missile Evasion Algorithm

The open loop missile evasion algorithm is based on simplicity and the results of maneuver analysis. Any algorithm that must be recalled from memory in the heat of battle must be fairly simple. Any algorithm that cannot be easily memorized and recalled by the pilot has no place in todays single-seat fighters. Besides, any look-up table has little value since the pilot has absolutely no time to look down into the cockpit. Fortunately the maneuver analysis and simulation results tend to indicate a fairly simple algorithm.

The missile evasion algorithm requires that only two decisions be made by the pilot. Following some indication of a missile launch, the first question the pilot must answer is, "Do I see the missile?" If the answer is "No", then the pilot should begin a maximum g jinking maneuver. This jinking maneuver need not be in any specified plane and the period should be as rapid as possible. The purpose of this maneuver is to attempt to create some type of resonance within the missile. The relative range when this maneuver is initiated

appears to have little effect on the miss distance. Pilots sometimes take evasion action without actually seeing the missile when warned of a missile launch from radar warning equipment or when directed by a wingman. The pilot may wish to make the first turn in a direction that might make a visual pickup of the missile possible. In any event, without a visual sighting of the missile the pilot has no way of estimating the time-to-go until impact or relative range so he should begin a rapid jinking maneuver as soon as possible. This is one branch of the algorithm.

The other branch of the algorithm centers around the other answer to the question "Do I see the missile?". If the answer is "Yes", then the pilot must estimate the time-to-go before impact. If the time-to-go before impact is less than one second then an immediate maximum g turn must be made perpendicular to the LOS vector. For a non-maneuvering target the range that corresponds to the one second is shown for all relative azimuth angles for each fighter in Fig 2.5. The miss distance for a perpendicular pitch up at one second TGO is also shown in Fig 2.5. If the time-to-go is greater than one second the pilot, can proceed as follows. With the missile in sight the pilot can estimate the relative azimuth and elevation of the LOS vector from the target to the missile. The pilot should roll the aircraft as necessary to align the lift vector with the unit normal formed by the cross product of the LOS vector and the target's velocity vector.

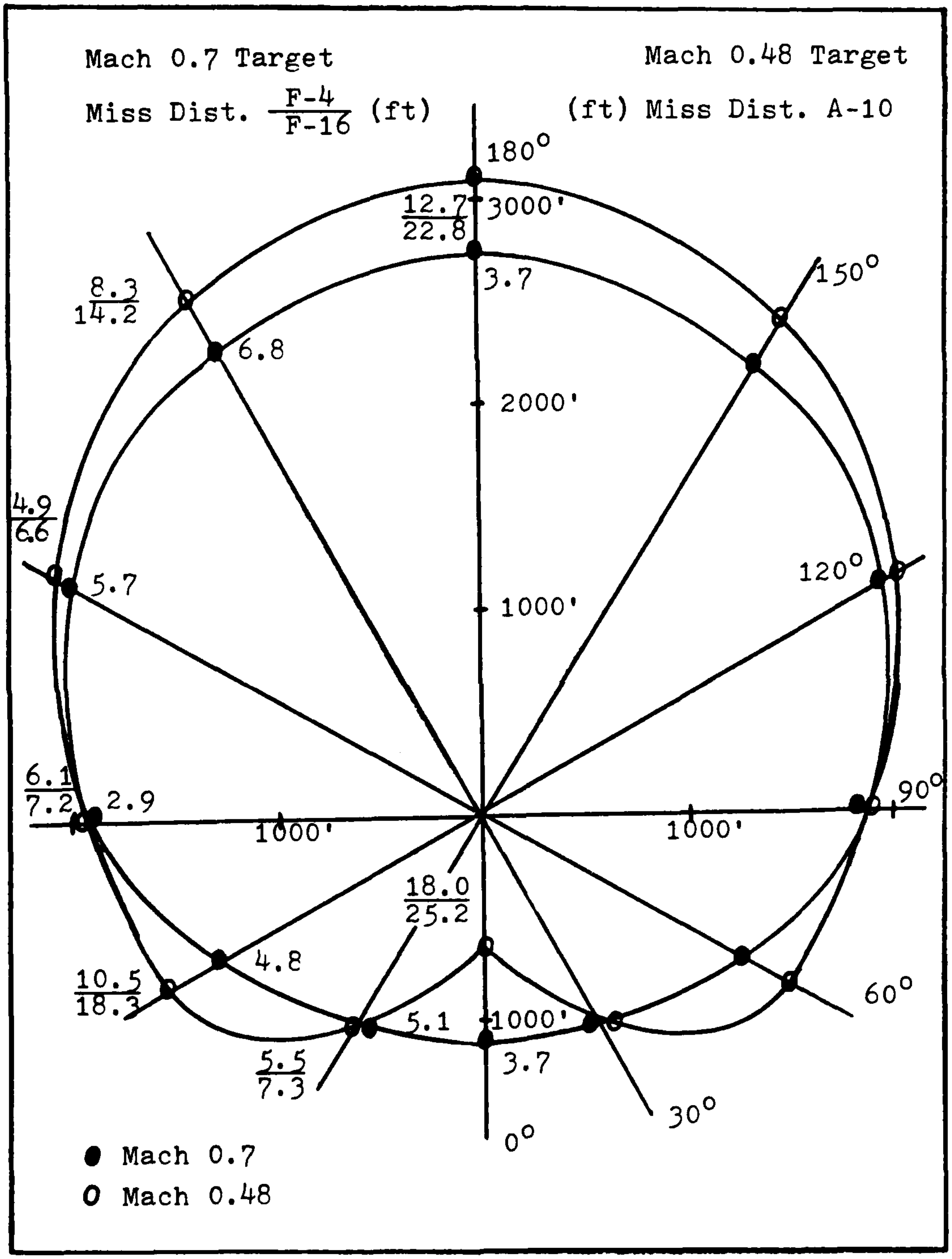


FIGURE 2.5 Relative Range and Miss Distance for 1 Second Time-to-go

$$\hat{u}_n = \frac{\overline{LOS} \times \bar{V}_t}{|\overline{LOS}| \cdot |\bar{V}_t|} \tag{2.6}$$

This will give the target an acceleration normal to the line-of-sight. The pilot should then perform a jinking maneuver using 180 degree reversals and maximum g available as quickly as possible. Assuming the pilot can keep the target in sight during this maneuver he should time the last reversal to occur about one second before the expected impact. This maneuver will give the pilot the best miss distance against a proportional navigation guided missile. (Fig 2.6)

The algorithm presented is simple and the maneuvers are shown to be the best by the simulation results. The algorithm is simple enough to be memorized for use in a high stress environment. The computer simulation results show that jinking or a switching maneuver gives better miss distances than a barrel roll or a simple maximum g turn. The results also show that a jink made perpendicular to the intercept plane with a last second reversal gives the best miss distance of all maneuvers examined. A more detailed look at these two maneuvers is presented in Chapter IV to support this open loop missile evasion algorithm.

These two maneuvers were tested with an F-4 against

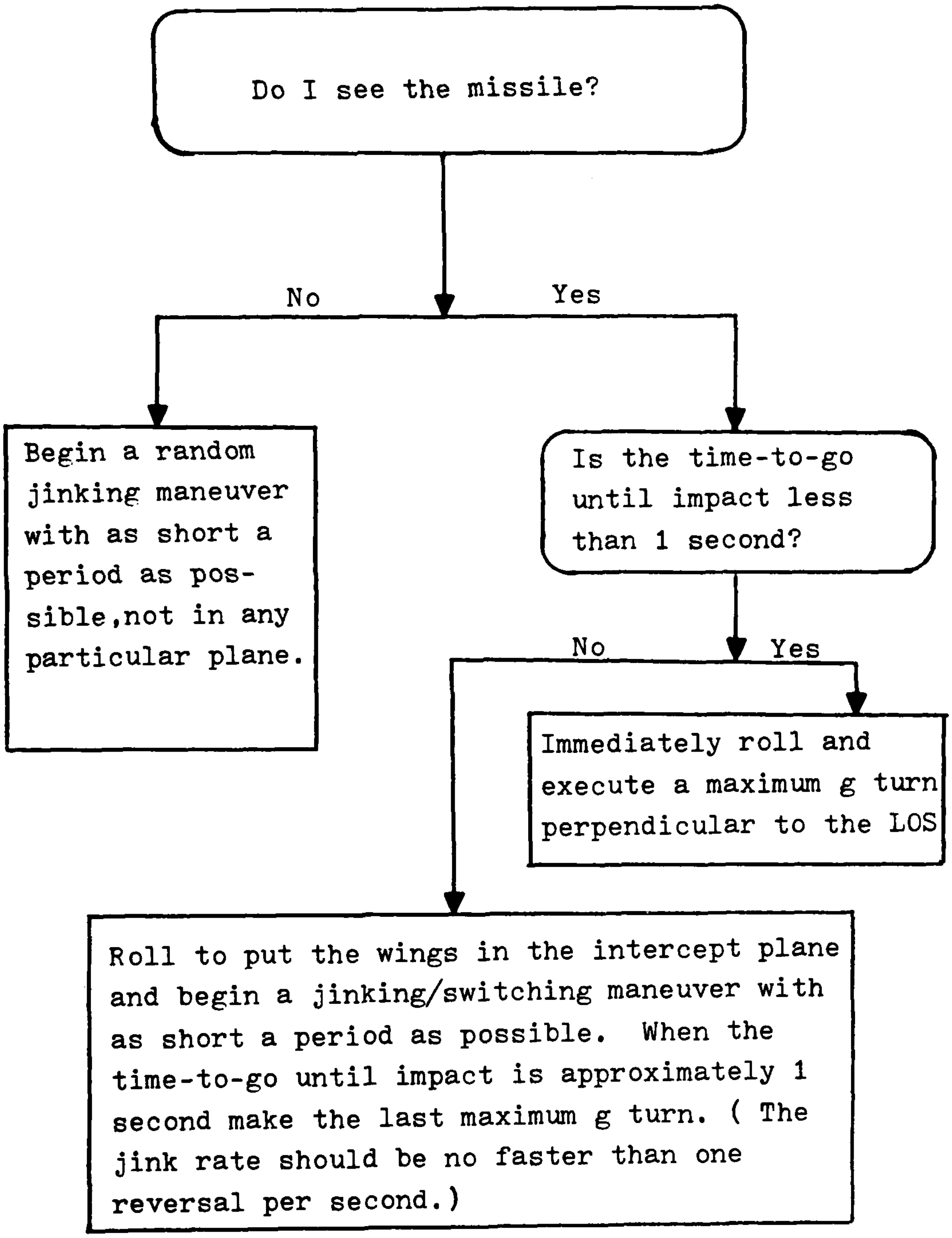


FIGURE 2.6 Missile Evasion Algorithm

missiles with structural g limits of 10 and 20 g's and the results are found in Appendix A. As expected, the average miss distance increased for both maneuvers as the missile g limits decreased. Also, the maneuvers were tested with an F-4 at a altitude of 25,000 ft with the same other initial conditions for comparison. In this case the average miss distance decreased about twenty percent for the rear and abeam aspect and remained about the same for the front aspect. Again, this is expected since at higher altitude the missile does not slow down as quickly and the target cannot perform as well. Those results are found in Appendix A. Finally, two and three dimensional diagrams of six different engagements are provided in Appendix B.

The missile evasion algorithm was based on target maneuvers that resulted in the largest miss distance. Target maneuvers were analysed with respect to missile guidance law and strustural limit parameters to establish the maneuver's potential for creating a miss. To verify the analysis results a computer simulation was used to calculate a miss distance for each target maneuver. This computer simulation, TACTICS IV, is discussed in the next chapter.

III The Computer Simulation, TACTICS IV

TACTICS IV Program

TACTICS IV is a specialized version of the TACTICS program developed at the Rand Corporation in 1969 and it is the computer simulation used to evaluate the miss distance values for the target maneuvers tested. It is designed for simulating missile/target engagements involving relatively short ranges so that flat earth representations are adequate. It can be used as a three degree of freedom (DOF) or six DOF simulation. It was used as a three DOF simulation for this thesis. Gravity, thrust and aerodynamic forces are modeled to act on the missile and target which are both assumed to be point masses. There are several open loop and one closed loop maneuver programmed for the target. (Ref 8) Changes were made at AFWAL so that the missile seeker model permits the seeker to be simulated with specific capabilities. (Ref 6) The program is built around subroutines and two subroutines were modified by myself.

Target And Missile Forces

The forces modeled for the aircraft are very simple compared to the forces modeled for the missile. Gravity is always assumed to be constant and perpendicular to the flat earth. Both thrust and drag on the target can be indirectly varied by using a thrust-to-drag (T/D) ratio, otherwise, it is assumed that thrust equals drag for level flight. The missile is provided with a two stage booster using specified burn rates, thrust and burn times. Drag on the missile is

determined using a given cross sectional reference area, a calculated coefficient of drag, as well as, computed speed and density. Missile lift is also computed in the same way and with the same cross sectional reference area as drag. The lift and drag coefficients are derived from the input data shown in Table 3.1, where both are entered as functions of mach number and the coefficient are determined by interpolating between table values.

Guidance Laws

The guidance algorithms for both missile and target compute accelerations for the point masses. The target can be moved by selecting one of eight maneuvers. These maneuvers are

1) Straight Level
2) Horizontal Level Turn
3) Smart Target
4) Split S/Vertical Climb
5) Three Dimensional Turn (with specified bank angle)
6) Maximum Acceleration (MAXACC)
7) Barrel Roll (with specifiied roll rate)
8) Three Dimensional Jink (with specified bank angle and period of jink)

The maneuvers are self explanatory except for the Smart Target and MAXACC maneuvers. For the Smart Target maneuver the target decreases altitude and turns into the missile when attacked from behind, while the target increases altitude and turns into the missile when attacked from the front.

TABLE 3.1

Input Lift and Drag Coefficient Table

Mach Number							
0.20	0.80	1.50	2.00	2.35	2.87	3.95	4.60
C_{do} Boost Phase							
0.185	0.190	0.70	0.56	0.48	0.403	0.28	0.23
$C_{n\alpha}$ (per deg)							
1.04	1.04	1.04	0.93	0.86	0.90	0.90	0.87
$C_{m\delta}$ (per deg)							
0.755	0.755	0.755	0.413	0.288	0.180	0.108	0.090
α/δ							
0.93	0.93	0.93	0.64	0.62	0.42	0.33	0.31
ΔC_d Coast Phase							
0.116	0.127	0.198	0.162	0.141	0.113	0.070	0.051

(Ref 8:48)

(Ref 8:41) Subroutine MAXACC is a closed loop maneuver with the target using known state information of the missile to determine a target normal acceleration that will maximize attacking missile commanded acceleration. (Ref 8:44) The missile uses the classical proportional navigation guidance law. The navigation proportionality constant, λ , can be made constant or entered as a function of time. It was entered as a constant value and made equal to four in the reported simulations. All of the missile and target values used are listed in Table 3.2.

Two changes were made to the original guidance laws found in TACTICS IV. The first, changed the jink maneuver from a horizontal plane switching motion to a switching motion in a plane defined by a bank angle. This allows one to examine a switching maneuver in planes other than horizontal. The other change to the basic TACTICS IV program provides for a last second switching maneuver to occur along with the three dimensional turn or jink maneuvers. This allows one to simulate a last ditch, maximum g turn away from the expected missile flight path with a different bank angle. Both of these changes to the target guidance algorithm are presented in more detail in Appendix D.

Missile Accuracy

For the results to have any meaning a baseline miss distance must be established. This was done by allowing the missile to intercept two targets that did not maneuver. One target was at 0.7 mach and the other at 0.48 mach and both

TABLE 3.2 Missile Parameters

Weight (lb)	W	350
Reference Area (ft^2)	A	0.349
Structural G Limit		30.0
Initial Velocity at Burnout (mach)		2.5
Proportional Navigation Constant	λ	4.0
Lead and Lag Autopilot Time Constants	τ_1, τ_2	both 0.1
Natural Frequency for Autopilot Transfer Function	ω_n	6.0
Damping Factor for Autopilot Transfer Function	ξ	0.7
Maximum Angle of Attack (deg)	α_{max}	21.8
Moment of Inertia, Pitch Axis (slug-ft^2)	I_y	94
Static Margin of Missile (ft)	X_{ref}	0.25
Maximum Control Surface Deflection Rate (deg/sec)	$\dot{\delta}$	300
Roll Rate for Barrel Roll (deg/sec)	$\dot{\psi}$	90.0
Gimbal Rate Limit (deg/sec)		60.0
Gimbal Angle Limit (deg)		90.0
Integration Step Size (sec)		0.05

(Ref 8:121-126)

flew a straight and level path. The simulation started with the missile at 2.5 mach and 18,000 ft away. Seven different initial azimuth angles were tested with an average miss distance of 1.091 feet for the 0.7 mach target and 1.644 feet for the 0.48 mach target. Since the missile is gradually slowing the missile must compensate by constantly maneuvering to slowly increase the lead angle. Additionally, during the last 90 feet of intercept the missile simulates seeker head saturation so that no guidance commands are made to make corrections. These two factors are the reason that the miss distance values are not identically equal to zero for these non-maneuvering targets. The missile initial azimuth and miss distance for each case are listed in Table 3.3. Missile azimuth is zero degrees for a tail attack and 180 degrees for a head-on attack. These values can be used to evaluate the miss distances found for various target maneuvers.

Target Realism

A final check on the simulation to verify realism is to compare the turn radius for each fighter to see if it agrees with expected values. The target speed for each type of fighter was selected to be the corner velocity for that aircraft. Corner velocity is the speed all fighters want to maintain in any turn since it results in the best turn rate and turn radius. The g limit assigned to each fighter is the maximum g limit expected for that aircraft in a typical combat configuration (ie, external missiles, bombs, and electrical warfare pods.) In Table 3.4 one can see that the turn

radius calculated in this simulation compares very favorably with values listed in flight manuals.

TABLE 3.3 Missile Accuracy Check

Missile Azimuth (deg)	Miss Dist (ft) 0.70 mach	Miss Dist (ft) 0.48 mach
0 (tail)	0.135	0.974
30	1.116	1.160
60	0.076	1.402
90	1.700	1.540
120	1.455	1.420
150	2.943	2.928
180 (head-on)	0.217	2.086

TABLE 3.4

Comparison of Calculated and Actual Turn Radius

Fighter Type	Calculated Radius (ft)	Actual Radius (ft)
A-10	1792	1750
F-4	3148	3100
F-16	2335	2250

(Refs 13; 14; 15)

IV Analysis of Evasion Algorithm Maneuvers

To demonstrate that the maneuvers selected for the evasion algorithm are based on more than the results of a computer simulation, this analysis of those maneuvers is provided. The basic thrust of this chapter is to first show why the jink is the better maneuver and then to indicate why any maneuver should be made perpendicular to the LOS vector.

Why the Jink

The jink is a maneuver that has been frequently examined as an open and closed maneuver. Shinar (Ref 11) has examined this maneuver in detail. He has developed closed loop and open loop variations for the jinking/switching maneuver. Shumaker (Ref 12) also concluded that a bang-bang, switching maneuver was one way of maneuvering to increase the miss distsnce. Carpenter and Falco (Ref 5) state that a waeving maneuver with the reversal points dependant upon the relative range is the optimal closed loop evasion policy for most launch coordinates. These are but a few of the studies done which indicate that a jinking maneuver is the best or optimal maneuver to evade a missile using PN guidance.

One study by Besner and Shinar (Ref 1) was particularly interesting in that it attempted to relate the frequency for the jinking maneuver to the missile proportionality constant λ . They assume that this sinusoidal maneuver has a random phase or in other words is begun at a random relative range. They further assume that the missile has either

first order dynamics or second order non-oscillatory dynamics. Next they define a frequency, U, which is defined as

$$U = \omega_t \tau \qquad (4.1)$$

where ω_t is the frequency for target weaving and τ is the overall time constant from the missile dynamics. For the second order dynamics represented by

$$F(s) = \frac{1}{(\tau_1 s + 1)(\tau_2 s + 1)} \qquad (4.2)$$

the overall τ is the sum of τ_1 and τ_2. He finally concludes that the relationship between U and the proportionality constant λ is as follows.

$$U = \sqrt{\frac{\lambda - 2}{2}} \qquad (4.3)$$

Besner and Shinar maintain that given the proportionality constant and missile dynamics the optimum frequency for target maneuvering can be found with these equations.

By reasoning, one can see why a jinking maneuver should be effective against a PN missile. A PN guided missile attempts to establish a lead angle and then works to keep the line-of-sight rate at zero. Many studies have shown this guidance law to be the optimum for a constant turning or a constant

velocity target. Hence, to evade the missile the target must not maintain a constant turn. To keep the missile turning the maximum amount of time the target should turn in one direction only long enough for the missile to establish its lead angle then make a move to destroy that lead angle. A 180 degree reversal by the target will force the missile to make the largest angle change to establish the new lead angle, Fig 4.1. If this constant 180 degree switching were continued the missile would be forced to fly with a higher g load more often and would slow down faster. In addition, it might be possible to establish a resonant switching frequency that could result in some type of structural or mechanical limit being reached.

The objective of many studies on missile evasion maneuvers for a PN missile has been to determine a way to calculate a resonance frequency or switching pattern that will force an instability in the missile. Typically, missile seeker head gimbal movement and missile response to aerodynamic forces both exhibit damped oscillatory motion. A sinusoidal line-of-sight motion at just the right frequency might be able to cause a resonance in the seeker head gimbal and cause the gimbal rate limit to be exceeded. The normal acceleration command generated by the missile could oscillate in a sinusoidal pattern that might result in the missile reaching structural g limits, thus not being able to turn as quickly as needed. The three studies mentioned in the beginning of this chapter have each sought different ways to find that maneuver frequency or switching pattern. In every

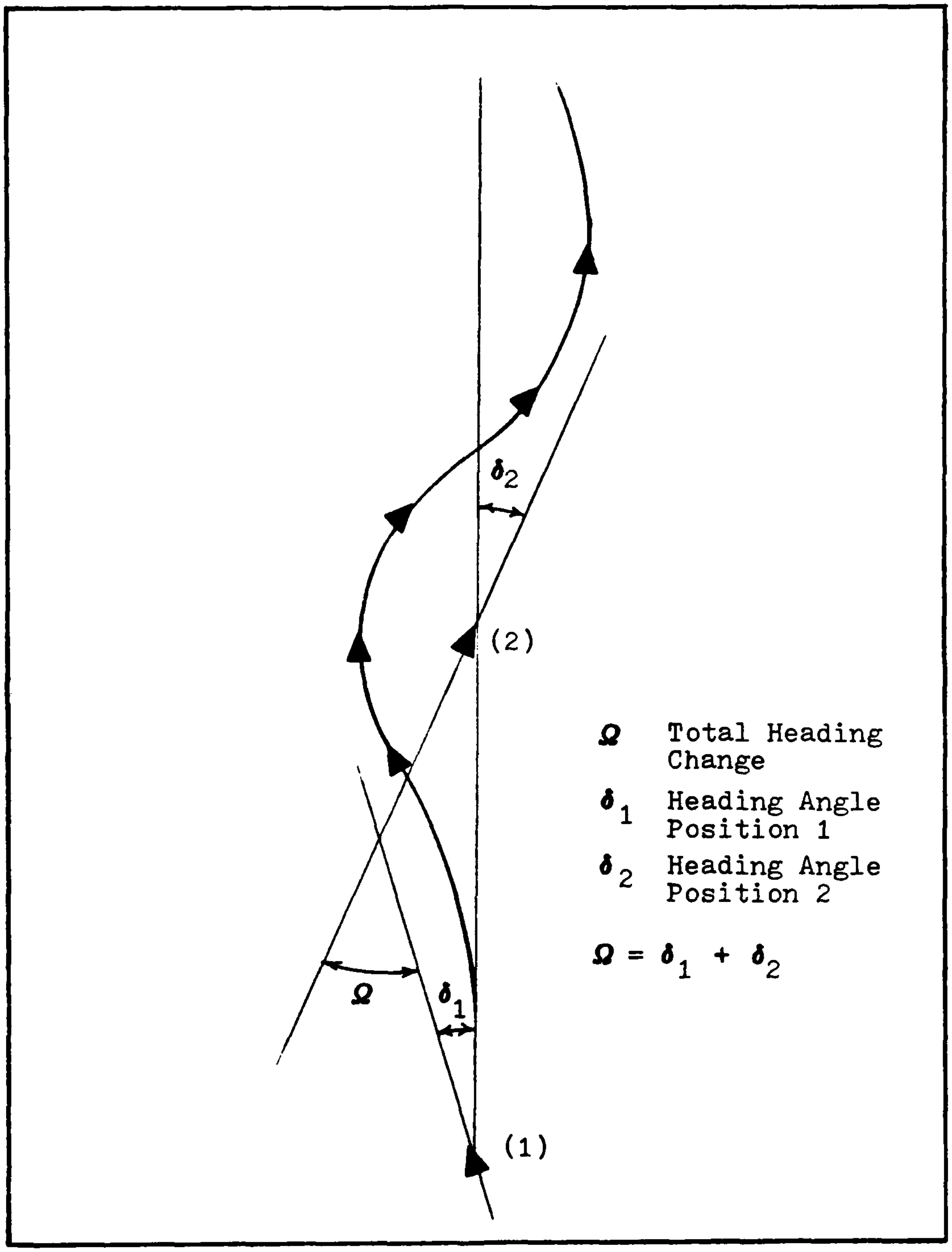


FIGURE 4.1 Target Reversal and Missile Lead Angle

case they analyze equations that are non-linear and rely on information that a pilot does not have. Since the pilot does not have access to accurate range and range rate data nor does he have access to data on actual missile dynamics or values, no attempt has been made in this paper to find a specific jinking frequency or pattern. However, there remains to be established a frequency range which will produce the best results for a switching maneuver.

In searching for a usuable jinking frequency range the work done by Besner and Shinar will be used as a starting point. First, remember that Shinar's results were based on non-oscillatory, second order dynamics. An approximate second order non-oscillatory model for the missile would be a system with τ_1 and τ_2 equal to 0.2 and the overall time constant, $\tau = 0.4$. Since values of λ range between 3 and 6 the values of U from Equation 4.3 range between 0.707 and 1.414. With τ at 0.4 the values of ω should lie between 1.768 and 3.536 radians/sec. This means a target should jink with a period of 3.6 seconds for a missile that has a $\lambda = 3$ and jink with a period of 1.8 seconds for a missile with $\lambda = 6$. The target flying against a missile with $\lambda = 4$ should jink with a period of 2.5 seconds according to the Besner and Shinar theory. These results should not be surprising since a larger λ value means a missile that responds more quickly, hence the target must perform a shorter period jink.

The missile sensitivity to the jinking period was checked with the computer simulation. The jink was perpendicular to the intercept plane and initiated at a relative ranges

of 10,500, 12,000, and 13,500 feet to allow the maneuver to cycle through several periods. The period was checked at 1, 2, 2.5, 3, 4, 5, and 6 seconds. The A-10 and F-16 dynamics were used for the analysis. As before the attacks were made with azimuth varying from a rear (0 deg) to head on (180 deg) attack in thirty degree increments. An average miss distance was calculated for each period and the results are listed in Fig 4.2 and 4.3. The oscillations noted in Figs 4.2 and 4.3 are of particular interest. For each curve the first peak occurs in a period range of 1.5 to 3.0 seconds while the second peak occurs at approximately twice the period of the first. This indicates that for a particular maneuver initiation range that a particular jinking period exists for achieving the largest miss distance. Also, it appears that as the initiation range is decreased, the integer multiple of that period produces a local maximum miss distance of reduced magnitude. Note that for the F-16 dynamics with a period of 2.5 seconds a maximum occurs for a maneuver initiation range of 10,500 feet while a minimum occurs for an initiation range of 13,500 feet. This shows that the maneuver initiation range must be accurately known to select a period to give the largest miss distance. Knowing the relative range and closure rate accurately an optimum period or switching pattern can be found. This is the basis for the closed loop studies by Borg (Ref 2), Carpenter (Ref 5), Hudson and Mintz (Ref 9), Shinar (Ref 11) and Shumaker (Ref 12).

If the miss distance values are averaged over the different ranges, the resulting curves (Fig 4.4) show the effects

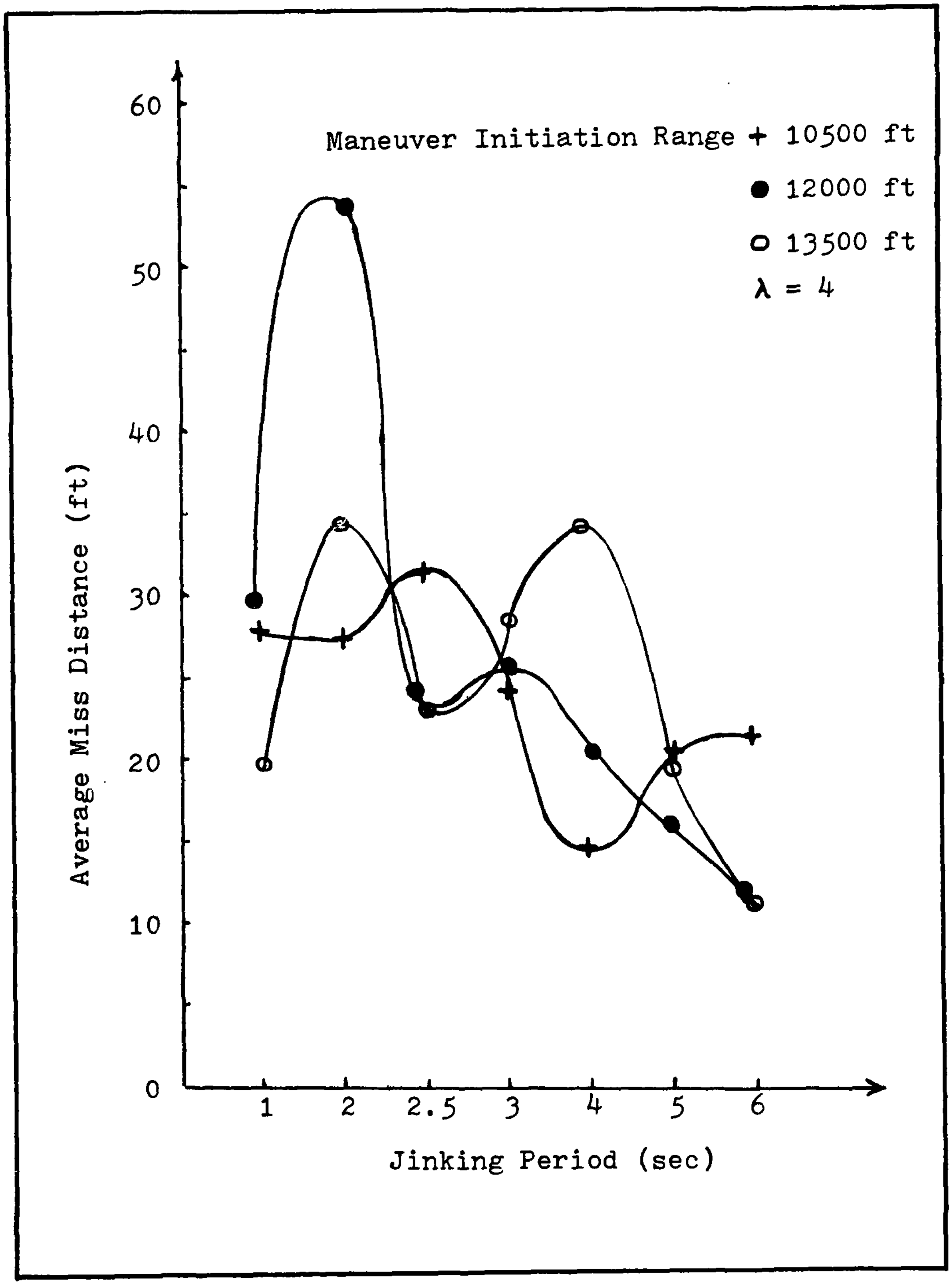


FIGURE 4.2 F-16 Miss Distance vs Period

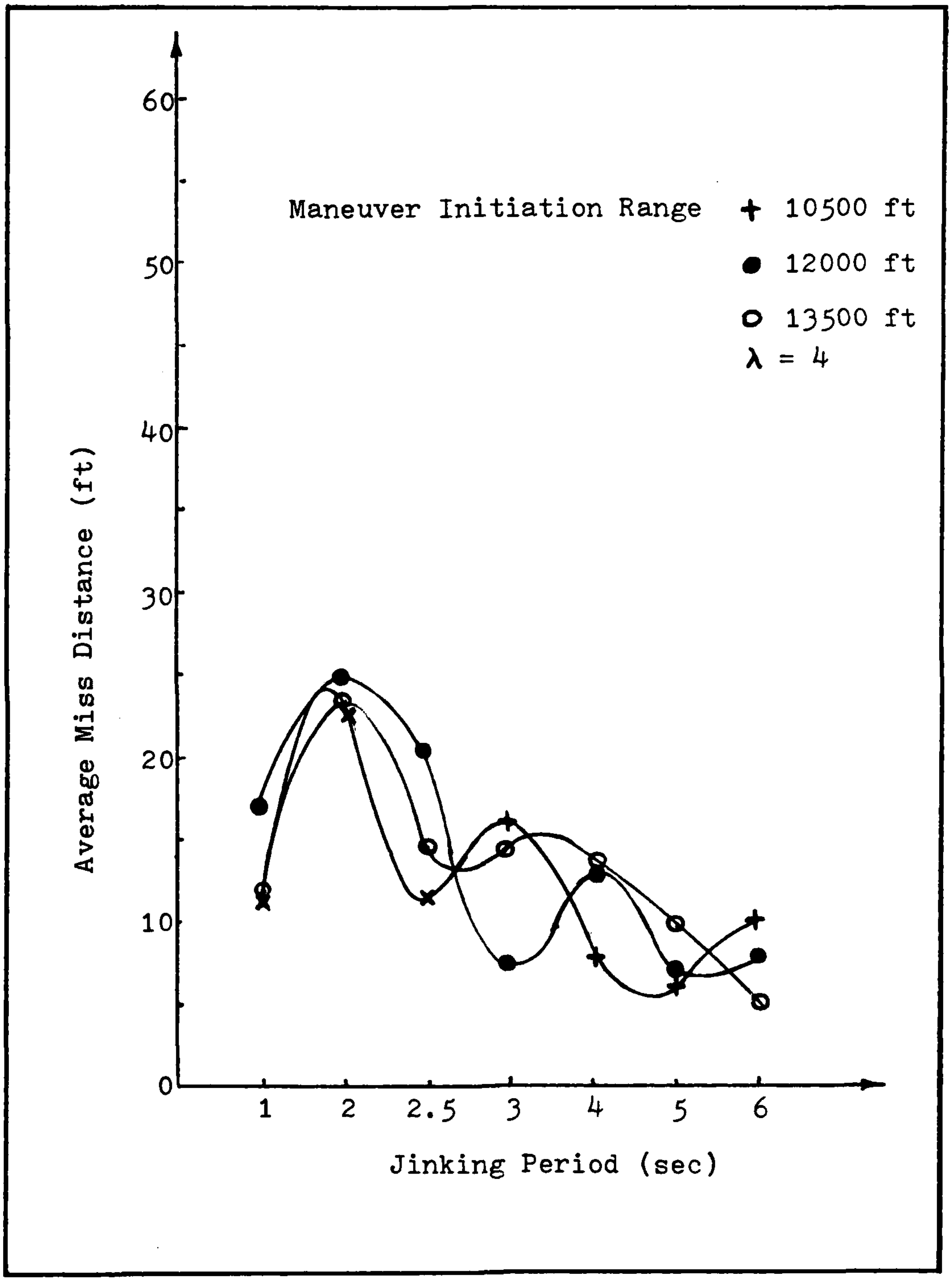


FIGURE 4.3 A-10 Miss Distance vs Period

of the jinking period independant of maneuver initiation range. These curves show a maximum miss distance for a 2.0 second period. Note that, as the period gets further from 2.0 sec., the average miss distance decreases. For the period of 1.0 sec the target is reversing direction every one-half second and there is little time for the target to move in space so the line-of-sight rate does not change much. For periods greater than 2.0 sec the missile is not being forced to reverse as often; therefore, the missile has a higher velocity at interception.

Since the period showing the maximum miss distance was at 2.0 seconds and not 2.5 seconds does not prove that the work by Besner and Shinar (Ref 1) is not valid since their work assumed non-oscillating dynamics and a constant speed missile neither of which was true for this simulation. These results do indicate that Shinar's results can help establish a frequency range for target jinking.

It appears that the pilot should try to reverse direction as quickly as possible with a limit of approximately one reversal per second. A complete range and azimuth analysis for all three fighters was done for a vertical jink with a 2.1 sec period. The miss distance results are reported in Appendix A. Realistically, a 2.1 second period is not possible today; however, it shows that a jinking maneuver made with a near resonance frequency can produce large miss distances.

The above analysis supports the claim that a jinking/switching maneuver is the best maneuver for a target to per-

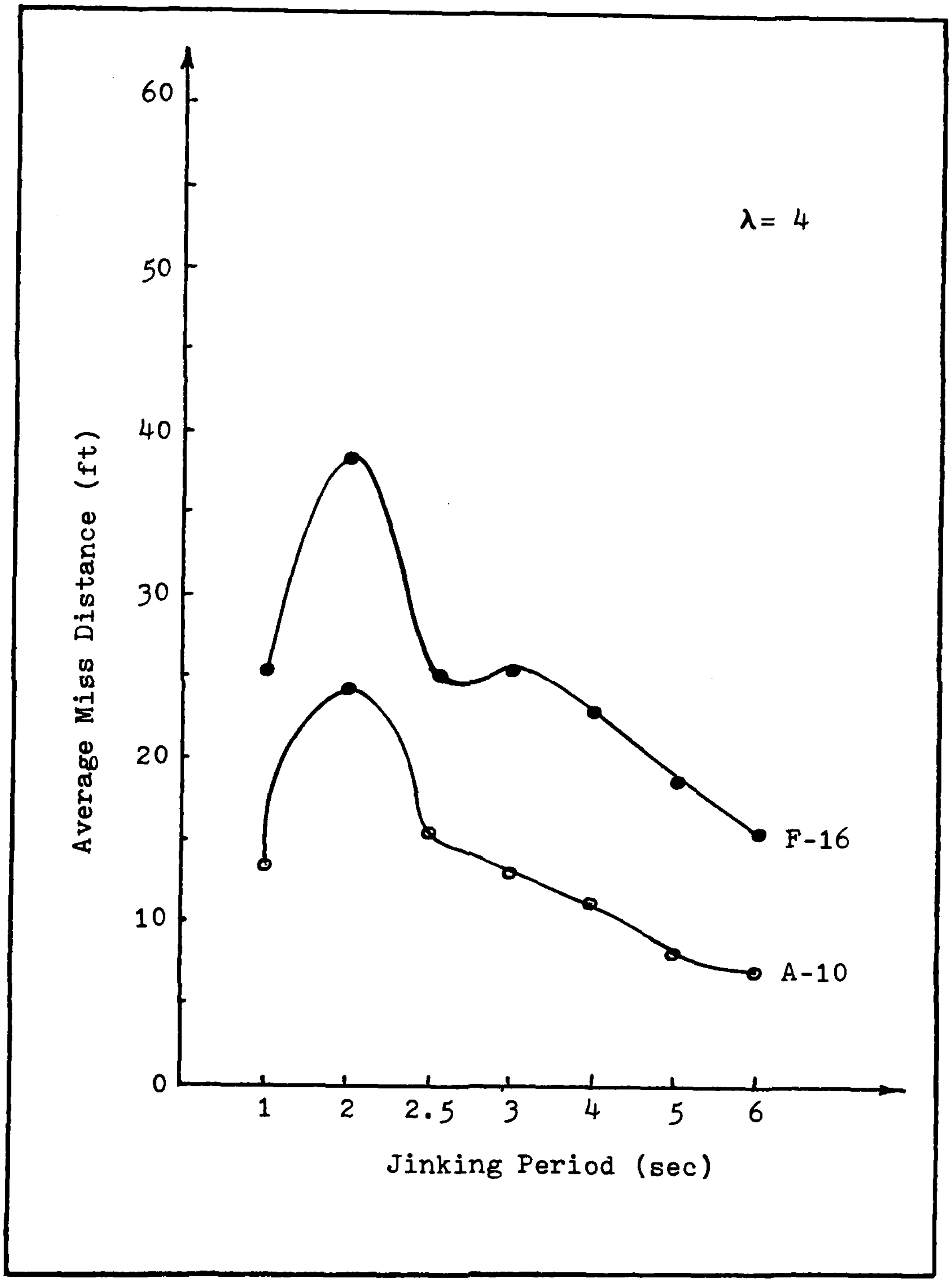


FIGURE 4.4 Average Miss Distance vs Period

form. The faster the switching can occur the better, up to the point where the target reverses its direction each second. One question remains unanswered. If the jink is the best maneuver, in what direction should this jink be performed? That question is answered in the next section.

Direction of the Jink

The orientation of the maneuver plane for the jink needs to be established to fully understand the target maneuver algorithm. Assumptions made in the analysis of the intercept geometry are as follows. As mentioned earlier the missile is assumed to have established its proper lead angle when the simulation begins. From this assumption the conclusion is made that the LOS vector, target velocity vector and missile velocity vector all lie in an intercept plane. It is further assumed that the initial LOS rate, $\dot{\theta}$, is approximately zero for the non-accelerating target. The following geometric analysis will look at an arbitrary plane to determine the angle ϕ , the angle between the LOS vector and target acceleration vector, that will maximize the LOS rate $\dot{\theta}$, Fig 4.5.

The arbitrary plane as shown in Fig 4.5 depicts the intercept at a specific instant of time. The LOS vector and it's first and second time derivatives are shown in the equations below.

$$\bar{R} = R\,\hat{e}_r \tag{4.4}$$

$$\dot{\bar{R}} = \dot{R}\,\hat{e}_r + R\dot{\theta}\,\hat{e}_\theta \tag{4.5}$$

$$\ddot{\bar{R}} = \ddot{R}\,\hat{e}_r + 2\,\dot{R}\dot{\theta}\,\hat{e}_\theta + R\ddot{\theta}\,\hat{e}_\theta - R\dot{\theta}^2\,\hat{e}_r \tag{4.6}$$

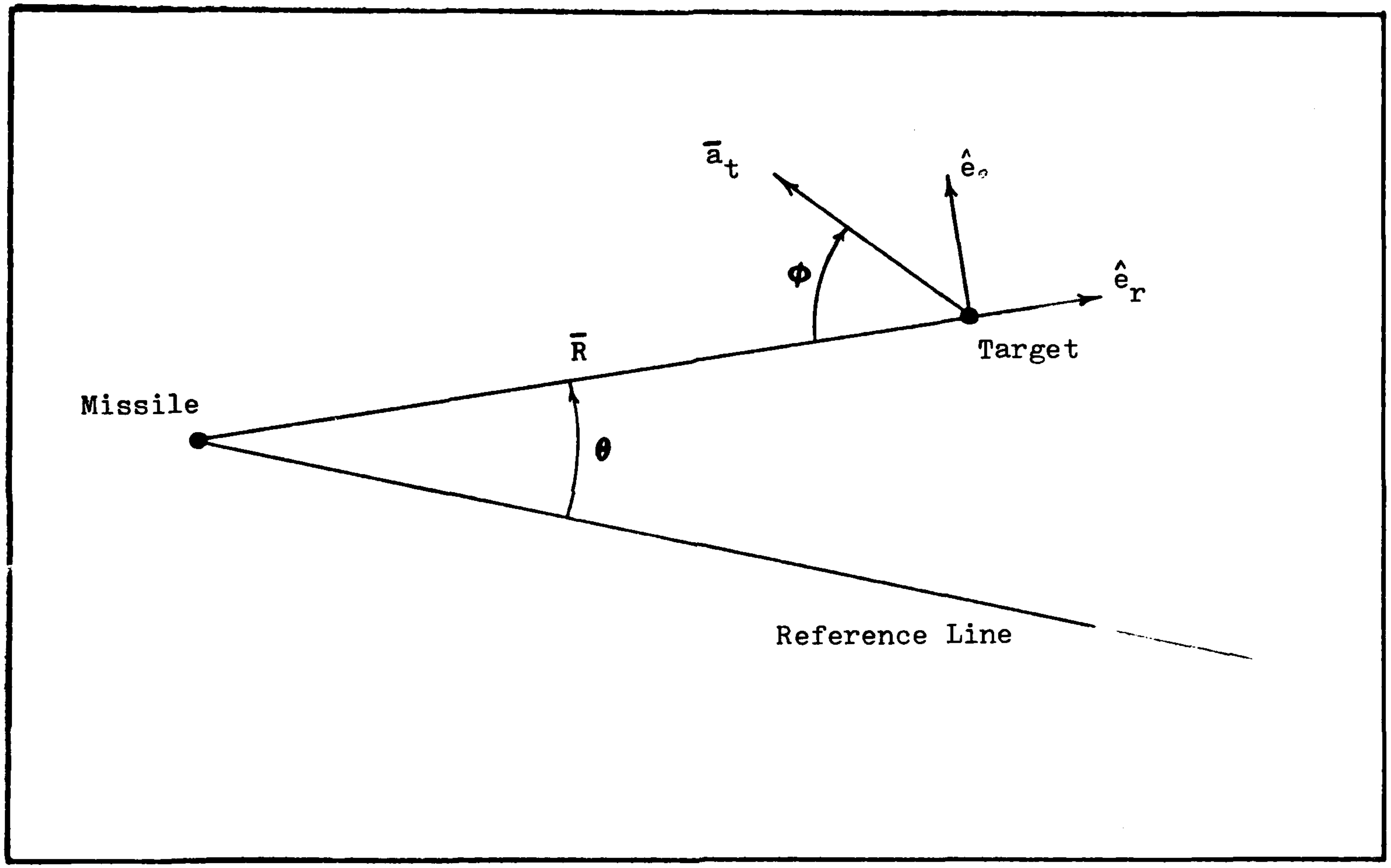


FIGURE 4.5 Intercept Goemetry in an Arbitrary Plane

The angle θ is measured from any arbitrary inertial reference line in the plane. The angle ϕ is measured between the LOS vector and the target acceleration vector. Dividing the LOS acceleration vector into components and setting them equal to the respective components of target acceleration gives

$$\ddot{R} - R\dot{\theta}^2 = -a_t \cos\phi \qquad (4.7)$$

$$R\ddot{\theta} + 2\dot{R}\dot{\theta} = a_t \sin\phi \qquad (4.8)$$

Next, let us assume that $\ddot{R}$ is approximately zero so that $\dot{R}$ is constant. Now, applying the D, which behaves like a Laplace transform, to $\dot{\theta}$ in Equation 4.8 we have

$$R\,D\,\dot{\theta}(D) + 2\,\dot{R}\,\dot{\theta}(D) = a_t \sin\phi \qquad (4.9)$$

or by factoring out $\dot{\theta}(D)$

$$\dot{\theta}(D)\,(R\,D + 2\,\dot{R}) = a_t \sin\phi \qquad (4.10)$$

$$\dot{\theta}(D) = \frac{a_t \sin\phi}{R\,D + 2\,\dot{R}} \qquad (4.11)$$

From Equation 4.11 it is easily seen, that to maximize $|\dot{\theta}|$ that $|\sin\phi|$ must be maximized; this means that ϕ should be ± 90 degrees to achieve the maximum LOS rate. Therefore, the target should accelerate perpendicular to the LOS vector to result in maximum missile g's. (Ref 7)

Several studies on missile evasion similarly indicate

that an orthogonal acceleration is needed to maximize the LOS rate. In Shumakers report he states, "One can conclude that no matter what the target angle or inclination of the initial intercept plane may be, it is always best to maneuver orthogonal to the plane of the initial intercept. Moreover, that orthogonal direction which takes advantage of the assisting force of gravity is the better choice." (Ref 12:24) He further states that the aircraft should keep its wings in a plane defined by the LOS vector and the missile's velocity vector such that the lift vector is orthogonal to that plane. (Ref 12:84) Since the assumption is made that the missile begins on the correct intercept course the LOS vector, missile velocity vector and target velocity vector are all coplanar in the initial intercept plane. A unit normal to the intercept plane can be formed by the cross product of the LOS vector and target velocity vector.

Since the lift vector is the major acceleration force acting on the target aircraft the lift vector should be aligned with $\pm \hat{u}_n$.

$$\hat{u}_n = \frac{\overline{LOS} \times \overline{V}_t}{|\overline{LOS}| \cdot |\overline{V}_t|} \tag{4.12}$$

By jinking in this orthogonal direction the maximum LOS rate will be created during each turn. The final last second maneuver should also be done in this same plane to maximize the LOS rate and to move the aircraft away from the

impending collision point as quickly as possible. There should be little doubt that evasive maneuvers should be done so that the movement is perpendicular to the line-of-sight vector.

V Conclusions and Recommendations

The Open Loop Evasion Algorithm

Several studies have been done to find a closed loop evasion maneuver to optimize the miss distance for a PN guided missile. (Refs 1; 2; 5; 9; 11; 12) Those studies assume that the target has state information that is presently not available. This study has examined classical fighter maneuvers in an attempt to find those promising maneuvers that produce the best miss distance for an open loop system. The only input parameters to the target are assumed to be relative range, azimuth, elevation, and an estimated time-to-go until impact. For any of those inputs to exist the pilot must have visual contact with the missile during some portion of the attack. Using these inputs and a simple closed loop missile evasion algorithm a pilot can select the best evasion maneuver to perform.

The evasion algorithm is simple so that it can be memorized for the use in combat. The algorithm has three different maneuvers which are selected based on two decisions. First, the pilot decides if the missile can be seen. If the pilot does not have visual contact with the missile he should perform a maximum g jinking/switching maneuver in any direction as rapid as possible. If the pilot does see the missile then a maximum g jinking maneuver should be done with as short a period as possible in a plane perpendicular to the LOS vector. Assuming the pilot keeps the missile in sight during these reversals a final reversal should be done

when the estimated time-to-go until impact is approximately one second. If the pilot, after seeing the missile for the first time, decides that the time-to-go is one second or less the maximum g turn perpendicular to the LOS vector must be made immediately. This is the entire open loop missile evasion algorithm, which gave the best miss distance for those cases studied using a missile with a proportional navigation guidance law.

Recommendations

The results of this study go beyond the formation of a missile evasion algorithm. The miss distance for the best maneuvers inicate that maneuvering alone will not insure the aircraft's survival. In chapter II and in Appendix A the miss distances calculated from the TACTICS IV simulation for the vertical jink with a 3.75 second period and the vertical jink with the last second reversal represent the types of miss distances one can expect using the best maneuvers. The missile used in the simulation is very realistic and represents the type of advanced missiles that exist today. Most of the average miss distance values for the vertical jink with a last second reversal were in order of 20 to 30 feet; they represent the best values obtained by the target maneuvering alone. Surely, more than target maneuvering is needed to insure aircraft survival from a missile attack.

One thing that can be done is to provide a system that will be able to provide accurate missile state information for use in an automated closed loop evasion algorithm. As

mentioned before, work has already been done to develop closed loop evasion algorithms against PN guided missiles. A radar/infrared package that can track the missile in flight and provide reliable range, azimuth, elevation, and range rate information in real time would be a big improvement. With that type of sensor information a computer and electronic flight controls the aircraft could be flown in a optimum flight path to avoid the missile. Optimum maneuvering should be able to produce two or three times the average values found for the vertical jink with the last second reversal. The type of missile tracking system suggested does not yet exist, other equipment does exist that must be used to help increase the miss distance.

Electronic countermeasures equipment existing today has been used successfully in the past; it must be used in the future if fighters are to acheive miss distances that are outside the missile's warhead lethality range. Specifically, jamming pods, chaff, and flares must be used along with smart aircraft maneuvering to increase the miss distance. Unfortunately not all operational fighters are equipped to carry jamming pods,chaff, and flares. All fighters made in the future should be built so that they are equipped to carry and use these countermeasure devices. If a missile using proportional navigation, is launched within parameters (ie, range, range rate, and valid seeker head lock-on) and has the few seconds needed to establish its lead angle, any fighter aircraft will be hard pressed to avoid damage by evasive maneuvering alone.

Finally, the target maneuvers presented here were done against a singe missile. A future study should examine open loop maneuvering against multiple threats. The study should examine target maneuvering to avoid two or three missiles launched seconds apart. Another study should attempt to find a pattern for target maneuvering that could be used to prevent a missile operator from being able to achieve satisfactory launch parameters such that either the missile cannot be launched or it is launched with initial parameters already near operational limits. The results from these two additional studies would further provide valuable tactical information that fighter pilot's could use to avoid enemy missiles.

For future studies TACTICS IV may be used as a simulation, but one should look for a more sophisticated simulation that provides better modeling. In TACTICS IV the target model is far too simple and future studies should use a better model when looking for specific target maneuvers against PN missiles. TACTICS IV is still useful when looking at a broad class of target maneuvers or sensitivity ranges.

APPENDIX A

SIMULATION MISS DISTANCE DATA

The miss distance data collected for the eight target maneuvers mentioned in Chapter II is listed in this appendix. The miss distance (in feet) is listed in tabular form for target maneuvers initiated at relative ranges of 3000, 6000, 9000, 12000, and 15000 feet and with initial relative azimuth angles of 0° (tail attack), 30°, 60°, 90°, 120°, 150°, and 180° (head-on attack). Additionally, the miss distance data for the 2.1 second period jinks, 10g and 20g missiles and engagement at 25,000 feet altitude is presented. The data is arranged as follows:

Tables A-1 through A-4 ..... A-10 Maneuvers

Tables A-5 through A-8 ..... F-4 Maneuvers

Tables A-9 through A-12..... F-16 Maneuvers

Table A-13 ....Vertical Jinks W/2.1 Sec Period

Table A-14 ....F-4 Vertical Jinking Maneuvers Against a 10 G Missile

Table A-15 ....F-4 Vertical Jinking Maneuvers Against a 20 G Missile

Table A-16 ....F-4 Vertical Jinking Maneuvers at 25,000 Feet Altitude

Table A-1

Horizontal Maximum G Turn

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	0.189	1.413	0.588	1.077	1.584
30	2.588	1.863	2.430	1.082	3.412
60	2.109	2.274	1.294	1.528	2.955
90	2.134	1.758	2.629	3.837	3.054
120	2.538	1.337	1.807	2.019	3.004
150	5.865	2.730	1.806	3.123	1.931
Head-on	7.492	3.701	0.966	0.558	1.653

Barrel Roll at Roll Rate of 90 deg/sec

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	2.681	1.712	1.660	1.795	4.432
30	3.652	2.229	2.500	2.497	0.316
60	5.463	2.538	2.906	2.414	1.640
90	7.613	4.363	3.484	1.851	2.095
120	7.762	4.295	5.341	6.122	1.417
150	5.740	6.199	7.762	8.566	0.503
Head-on	7.111	10.312	9.922	10.526	2.086

Table A-2

MAXACC (Closed Loop Guidance Law)

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	1.970	1.723	7.427	1.245	2.159
30	6.679	1.321	1.761	2.109	0.189
60	8.723	0.975	2.131	1.533	0.631
90	9.344	2.026	0.877	0.752	1.417
120	4.506	1.179	1.223	3.280	0.797
150	8.074	5.360	3.934	6.698	4.489
Head-on	11.329	3.108	6.870	3.649	6.008

130 deg Bank, Maximum G Turn w/180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	19.336	10.409	7.859	2.582	21.963
30	18.028	8.006	8.913	4.782	0.979
60	10.925	6.485	4.363	12.156	1.822
90	1.168	5.138	12.367	12.326	1.748
120	4.539	16.298	18.977	12.256	0.776
150	7.690	22.433	17.620	5.623	2.857
Head-on	9.383	20.548	8.906	3.366	2.666

Table A-3

Horizontal Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	10.587	5.169	8.159	7.857	10.276
30	1.069	3.608	4.075	3.498	11.881
60	2.008	0.185	3.505	2.013	2.292
90	2.134	8.734	1.142	0.381	9.573
120	2.538	14.219	5.440	12.272	0.745
150	5.863	8.061	6.180	17.023	4.029
Head-on	7.491	7.011	2.496	18.822	1.031

Vertical Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	13.900	5.743	11.761	7.429	11.950
30	9.381	11.800	3.072	8.744	10.383
60	2.228	2.236	14.707	8.089	7.614
90	3.295	6.053	19.885	4.325	4.257
120	2.869	25.171	5.388	12.301	7.688
150	3.504	13.854	4.008	25.308	3.990
Head-on	3.722	8.760	3.368	22.212	3.781

Table A-4

Horizontal Jink w/3.75 sec Period and 90 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	30.458	16.938	24.084	27.178	26.296
30	20.615	16.071	15.441	6.323	13.933
60	5.308	5.019	9.331	18.809	4.292
90	1.641	17.082	3.985	3.088	20.001
120	3.968	15.517	12.733	15.810	9.468
150	5.594	8.198	9.859	14.026	11.511
Head-on	7.520	7.088	8.353	16.400	11.211

Vertical Jink w/3.75 sec Period and 180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	39.909	25.371	35.640	40.422	3.959
30	31.210	40.208	23.130	3.970	14.187
60	2.886	19.180	17.798	11.657	15.600
90	14.181	2.081	24.765	20.270	2.744
120	11.906	17.045	24.140	2.414	16.441
150	13.356	6.511	17.066	10.487	21.978
Head-on	13.540	15.575	12.517	8.820	17.372

Table A-5

Horizontal Maximum G Turn

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	0.487	0.488	0.509	1.211	2.686
30	0.558	0.728	0.990	1.613	3.726
60	1.187	1.277	2.755	3.958	3.372
90	1.832	3.336	2.310	3.220	4.689
120	3.988	2.147	2.456	2.396	3.338
150	12.743	4.362	1.417	3.463	0.354
Head-on	17.321	2.321	0.731	3.578	1.884

Barrel Roll at Roll Rate of 90 deg/sec

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	1.179	0.970	1.407	1.314	0.811
30	1.018	0.638	0.877	0.879	1.014
60	3.257	1.290	0.836	0.970	0.372
90	2.959	1.822	0.976	0.745	0.694
120	6.811	3.713	1.311	1.212	0.502
150	7.193	9.731	2.826	2.965	3.346
Head-on	10.323	11.676	0.217	0.398	0.594

Table A-6

MAXACC (Closed Loop Guidance Law)

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	3.574	15.977	4.112	1.534	Target
30	1.606	0.683	0.772	0.544	Hits
60	4.477	0.119	0.548	2.488	The
90	12.946	0.427	1.241	2.164	Ground
120	5.451	1.566	0.448	0.380	No
150	15.227	8.427	3.442	2.029	Data
Head-on	21.929	4.025	1.874	7.111	

130 deg Bank, Maximum G Turn w/180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	4.490	1.407	6.029	16.681	21.296
30	2.490	1.629	10.738	17.667	18.576
60	13.729	11.523	15.181	15.197	10.394
90	9.259	12.071	10.750	3.738	4.186
120	4.881	1.956	10.275	13.538	10.427
150	8.584	17.101	18.026	15.696	8.040
Head-on	13.476	19.539	15.615	6.768	2.127

Table A-7

Horizontal Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	29.360	17.309	28.622	29.150	37.608
30	4.187	12.508	6.870	14.760	3.718
60	1.550	3.304	1.483	1.970	4.745
90	1.832	5.354	0.629	0.754	9.654
120	3.988	7.941	4.499	15.005	1.658
150	12.743	4.157	33.034	3.390	27.166
Head-on	17.322	2.555	28.024	1.197	34.165

Vertical Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	31.970	17.136	39.045	40.621	41.390
30	33.792	34.457	31.944	39.892	7.964
60	18.362	15.996	15.861	9.314	8.501
90	2.089	12.963	23.196	2.119	16.203
120	2.504	26.834	7.120	29.609	4.070
150	10.031	5.456	23.551	12.218	20.277
Head-on	12.744	0.751	31.888	2.259	32.454

Table A-8

Horizontal Jink w/3.75 sec Period and 90 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	39.260	4.372	13.163	19.918	14.995
30	13.607	33.147	12.735	13.690	8.794
60	23.547	11.921	9.572	6.063	28.208
90	3.020	17.989	17.153	5.114	23.808
120	6.308	11.154	14.578	24.672	11.614
150	10.156	18.032	21.257	17.797	14.777
Head-on	12.779	19.651	18.251	19.245	18.903

Vertical Jink w/3.75 sec Period and 180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	30.026	15.882	20.316	25.348	24.106
30	24.604	48.796	39.717	45.690	44.821
60	44.937	47.806	42.865	8.846	31.301
90	20.793	17.461	20.299	16.306	23.747
120	19.344	14.115	30.036	5.980	33.859
150	19.040	31.382	10.209	19.550	10.643
Head-on	21.493	35.885	2.770	30.005	1.227

Table A-9

Horizontal Maximum G Turn

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	0.739	0.779	2.906	4.226	5.050
30	1.366	1.571	3.606	5.102	6.764
60	0.134	2.357	5.168	5.743	6.653
90	2.583	3.782	6.189	5.692	4.058
120	8.181	4.582	5.087	2.258	3.260
150	22.107	4.974	1.189	2.256	2.828
Head-on	27.422	1.987	2.702	3.085	1.398

Barrel Roll at Roll Rate of 90 deg/sec

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	1.179	0.970	1.407	1.314	0.811
30	1.018	0.638	0.877	0.879	1.014
60	3.257	1.290	0.836	0.970	0.372
90	2.959	1.822	0.976	0.745	0.694
120	6.811	3.713	1.311	1.212	0.502
150	7.193	9.731	2.826	2.965	3.346
Head-on	10.323	11.676	0.217	0.398	0.594

Table A-10

MAXACC (Closed Loop Guidance Law)

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	3.604	18.912	3.267	0.759	Target
30	2.759	0.732	0.461	1.416	Hits
60	5.794	0.178	3.737	1.651	The
90	13.416	1.956	1.649	1.857	Ground
120	13.524	1.518	2.880	2.692	No
150	23.295	12.982	3.978	0.827	Data
Head-on	32.813	3.601	8.089	14.056	

130 deg Bank, Maximum G Turn w/180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	26.373	27.323	4.522	22.830	16.883
30	26.261	22.964	20.594	29.916	20.288
60	23.415	4.606	31.865	40.830	2.546
90	11.390	23.579	43.656	43.510	13.697
120	14.067	45.230	50.560	41.878	11.050
150	16.574	52.605	49.061	28.352	3.229
Head-on	24.267	48.299	33.164	6.690	5.436

Table A-11

Horizontal Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	39.005	18.869	38.715	50.608	42.372
30	17.281	16.455	13.017	2.288	7.184
60	0.366	1.353	5.932	0.638	11.059
90	3.188	20.203	2.778	1.537	14.481
120	8.221	9.612	26.337	21.681	4.702
150	22.096	3.619	51.790	4.052	45.418
Head-on	27.117	3.865	37.669	4.675	51.698

Vertical Jink w/3.75 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	38.661	25.425	61.402	59.783	20.639
30	39.752	40.129	53.282	45.362	27.375
60	26.423	28.444	20.992	16.099	4.394
90	3.317	7.296	41.602	3.320	7.455
120	1.927	38.437	8.621	48.936	5.986
150	18.762	7.868	38.599	20.408	37.577
Head-on	22.782	3.367	44.854	4.353	50.254

Table A-12

Horizontal Jink w/3.75 sec Period and 90 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	52.089	22.221	6.633	18.923	21.550
30	17.799	28.526	12.640	20.452	48.359
60	24.864	6.563	8.451	30.864	12.791
90	2.094	34.340	3.352	4.305	30.629
120	14.092	15.178	29.800	29.912	22.498
150	19.491	29.508	34.771	31.298	26.390
Head-on	22.841	30.162	28.958	27.851	30.239

Vertical Jink w/3.75 sec Period and 180 deg Reversal at one second TGO

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	44.688	67.738	12.783	23.827	66.028
30	73.247	63.860	57.817	67.547	26.364
60	43.306	63.247	42.036	39.573	67.048
90	46.253	26.230	28.760	43.025	40.292
120	33.616	10.929	51.607	3.866	58.550
150	31.034	49.500	16.419	28.316	20.162
Head-on	33.770	54.105	3.362	42.893	3.502

Table A-13

A-10 Vertical Jink w/2.1 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	27.444	30.272	25.685	25.334	26.551
30	25.931	22.586	25.756	31.644	28.358
60	16.014	36.457	13.459	30.302	38.898
90	25.108	28.212	1.756	23.476	32.037
120	7.971	25.184	30.201	31.312	33.279
150	3.416	9.180	6.805	14.356	14.867
Head-on	3.722	19.088	17.189	23.126	24.651

F-4 Vertical Jink w/2.1 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	10.888	3.396	20.893	10.369	6.551
30	10.383	26.499	24.529	26.607	2.368
60	34.414	37.116	15.070	41.186	25.415
90	36.308	14.741	37.781	49.269	45.343
120	8.301	13.966	28.119	31.949	27.770
150	10.031	34.950	33.756	39.047	35.702
Head-on	12.744	37.631	35.592	33.183	23.444

Table A-13 Continued

F-16 Vertical Jink w/2.1 sec Period

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	29.562	45.981	15.864	45.014	31.480
30	1.540	17.920	17.681	24.236	3.376
60	46.241	43.890	48.104	58.614	57.434
90	54.084	43.365	33.126	71.328	70.981
120	8.079	6.104	28.650	32.925	27.938
150	18.763	54.789	52.259	56.668	50.952
Head-on	22.786	54.961	50.742	46.600	28.119

Table A-14

F-4 Vertical Jink w/3.75 sec Period Against a 10 G Missile

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	10.257	50.024	19.246	46.647	24.044
30	49.182	24.436	40.489	29.371	27.541
60	24.633	31.849	13.901	58.451	58.014
90	28.269	73.966	27.409	40.068	77.662
120	34.727	7.270	81.794	30.410	51.939
150	32.810	50.379	60.900	76.409	47.079
Head-on	31.832	55.595	48.235	81.015	33.298

F-4 Vertical Jink w/3.75 sec Period and 180 deg Reversal at one sec TGO Against a 10 G Missile

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	42.454	57.070	65.545	58.832	61.296
30	55.696	35.660	14.337	17.395	45.818
60	24.143	19.500	31.395	49.533	62.684
90	64.257	33.227	13.005	59.053	44.773
120	48.280	16.022	48.469	64.539	61.315
150	48.541	53.386	14.871	29.429	46.301
Head-on	48.181	54.303	55.176	43.373	118.662

Table A-15

F-4 Vertical Jink w/3.75 sec Period Against a 20 G Missile

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	11.638	3.664	44.474	40.145	26.621
30	20.485	24.847	40.172	39.041	7.992
60	20.977	22.991	16.734	11.225	2.732
90	2.217	18.562	34.265	2.173	8.730
120	3.712	28.766	3.310	40.177	4.207
150	15.234	5.487	39.384	8.117	33.407
Head-on	17.977	0.644	42.097	13.994	40.304

F-4 Vertical Jink w/3.75 sec Period and 180 deg Reversal at one second TGO Against a 20 G Missile

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	34.809	50.690	54.031	45.881	63.740
30	60.707	43.084	45.574	43.463	23.935
60	24.711	45.235	19.747	36.080	59.989
90	40.365	23.630	22.474	42.269	32.637
120	29.635	2.823	39.544	6.984	47.259
150	28.387	41.807	12.134	27.467	13.560
Head-on	29.908	44.492	2.961	36.148	5.834

Table A-16

F-4 Vertical Jink w/3.75 sec Period in an Engagement at 25,000 ft Altitude

Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	16.891	4.538	5.849	6.106	16.489
30	9.279	17.179	16.873	12.115	11.581
60	2.617	4.068	10.678	12.238	17.722
90	5.766	19.079	22.073	4.142	4.032
120	2.025	23.660	8.072	32.291	5.777
150	9.936	7.013	21.442	19.177	10.802
Head-on	12.158	4.539	29.641	5.788	25.425

F-4 Vertical Jink w/3.75 sec Period and 180 deg Reversal at one second TGO in an Engagement at 25,000 ft Altitude

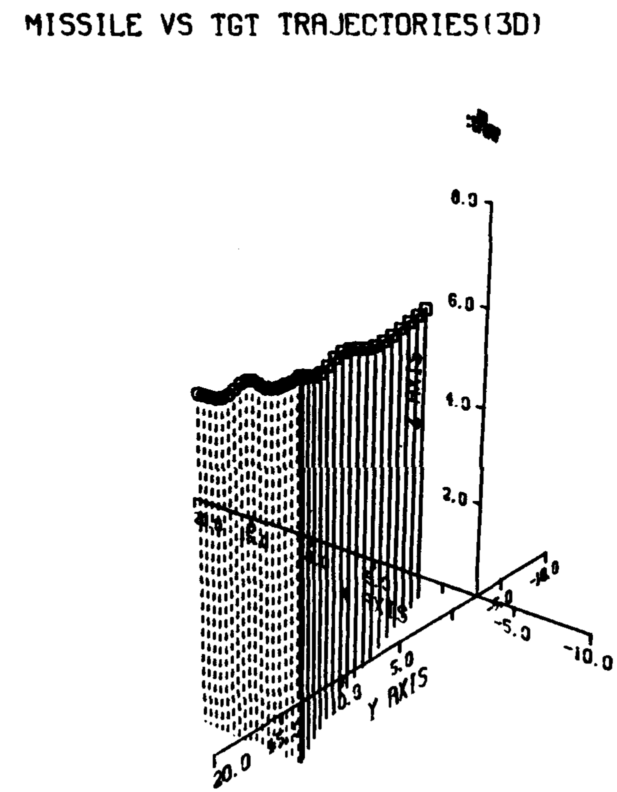
Azimuth (deg)	Range (ft)				
	3000	6000	9000	12000	15000
Tail	44.559	22.589	1.626	3.726	30.669
30	33.471	47.554	43.747	40.162	7.754
60	8.989	32.038	30.770	5.814	31.031
90	23.296	2.061	17.946	36.183	9.604
120	17.295	4.739	28.921	5.501	35.706
150	18.516	30.974	12.070	10.963	18.718
Head-on	20.550	35.172	4.611	26.067	7.056

APPENDIX B

GRAPHIC REPRESENTATIONS OF TARGET/MISSILE INTERCEPT SIMULATIONS

In this appendix two and three dimensional graphs of the target/missile intercepts are plotted. These graphs provide a view of the intercept to help visualize the target and missile maneuvering in inertial space. A graph of the missile velocity vs time is also provided for each maneuver so that one can see the effects of target maneuvering. The six different maneuvers are listed below.

1. Vertical Jink W/3.75 Sec Period and Reversal
2. Horizontal Jink W/3.75 Sec Period and Reversal
3. Vertical Jink W/2.1 Sec Period
4. Barrel Roll at 90 Deg/Sec Roll Rate
5. Horizontal Maximum G Turn
6. Vertical Maximum G Turn



Miss Distance 23.7 ft

FIGURE B-1 Vertical Jink W/3.75 Sec Period and Reversal

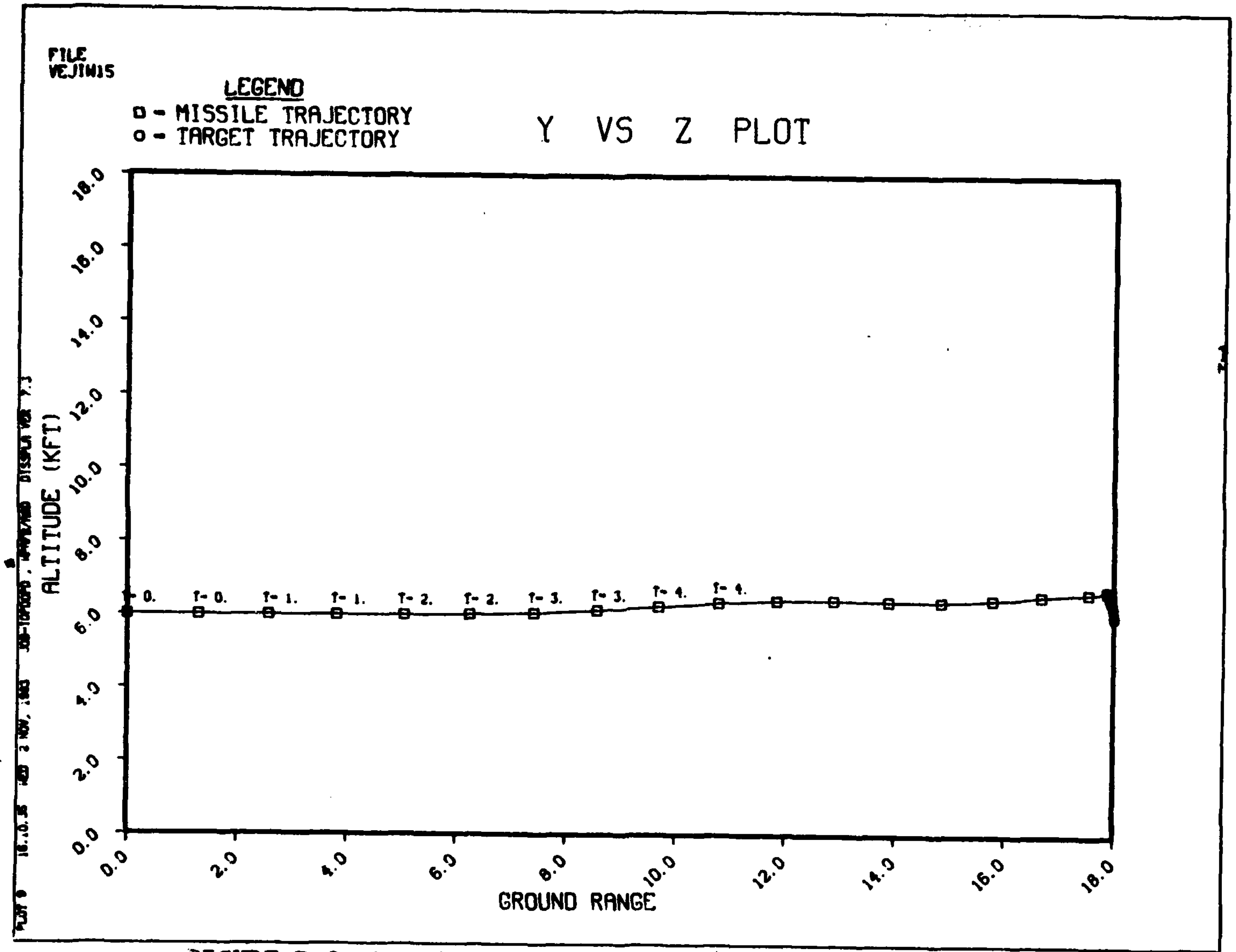


FIGURE B-2 Vertical Jink W/3.75 Sec Period and Reversal

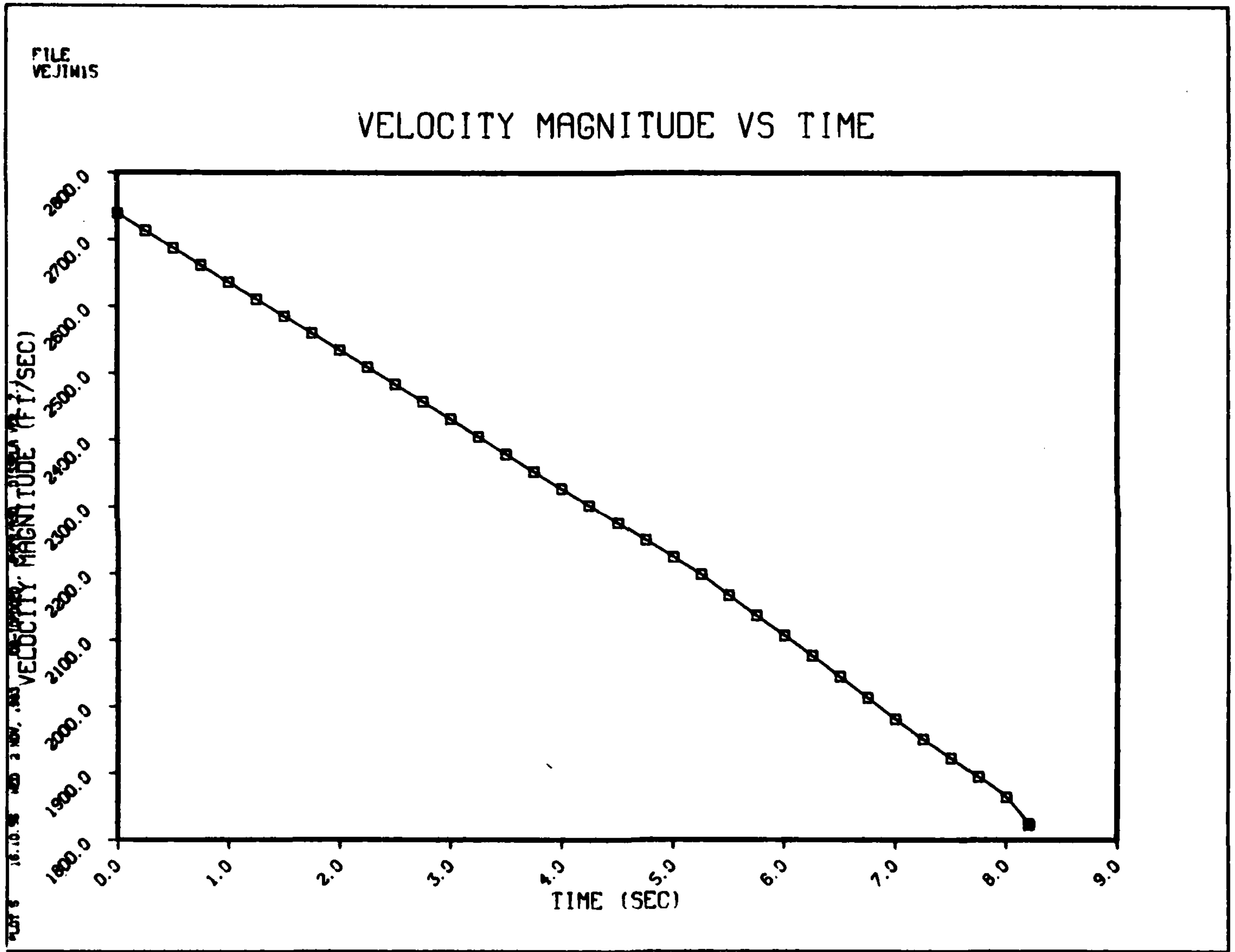
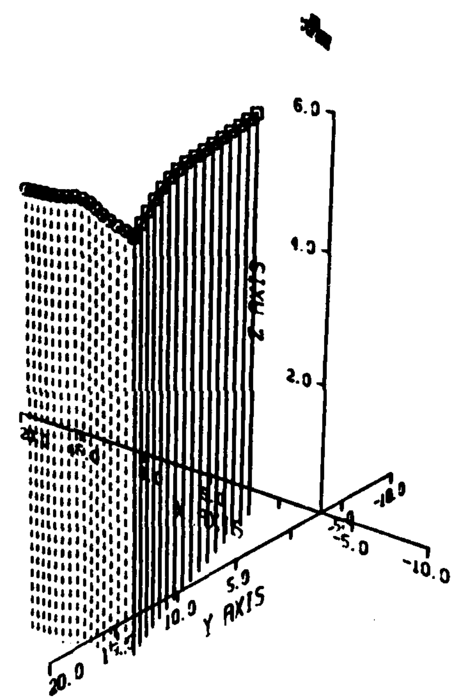


FIGURE B-3 Vertical Jink W/3.75 Sec Period and Reversal

MISSILE VS TGT TRAJECTORIES(3D)



Miss Distance 24.2 ft

FIGURE B-4 Horizontal Jink W/3.75 Sec Period and Reversal

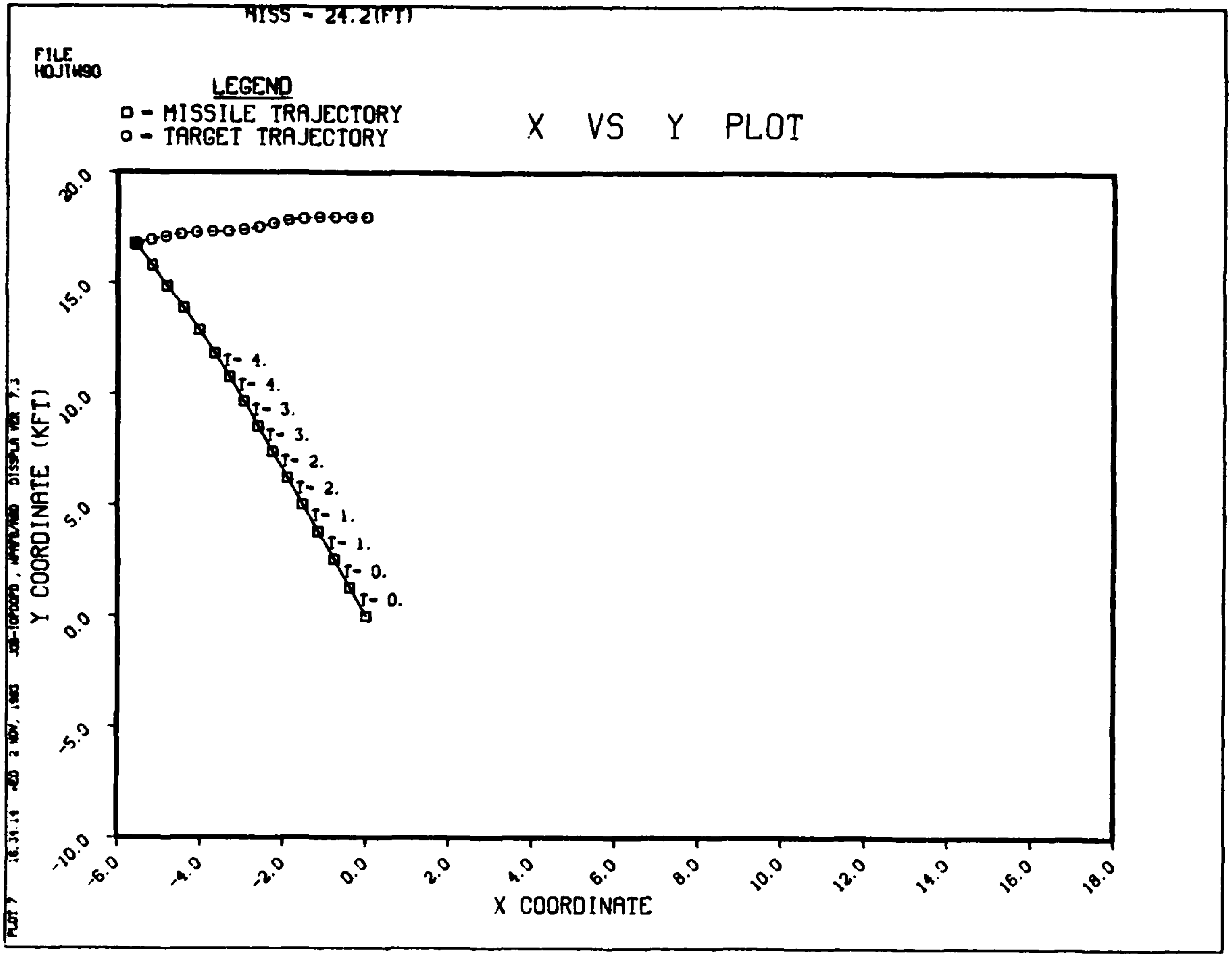


FIGURE B-5 Horizontal Jink W/3.75 Sec Period and Reversal

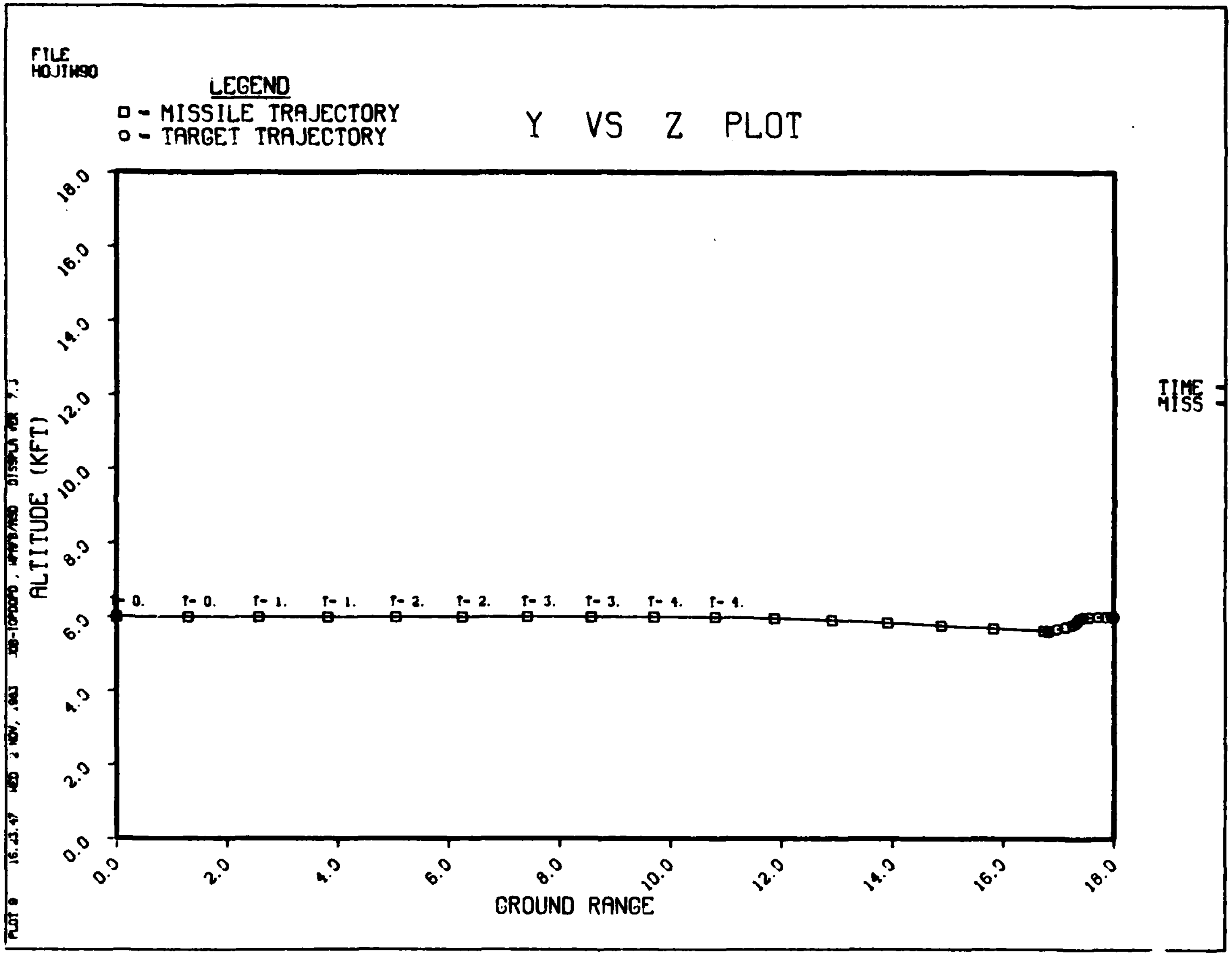


FIGURE B-6 Horizontal Jink W/3.75 Sec Period and Reversal

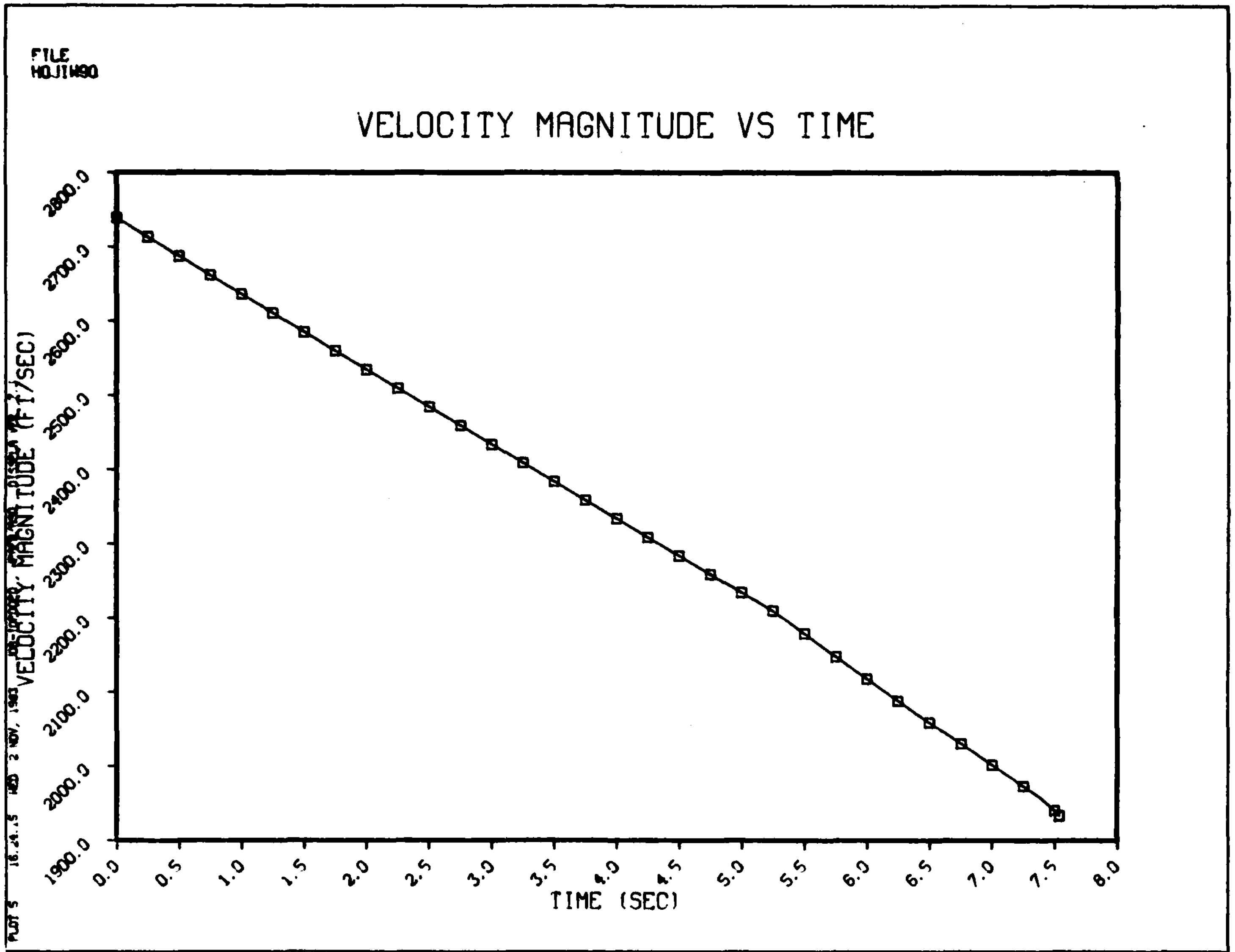
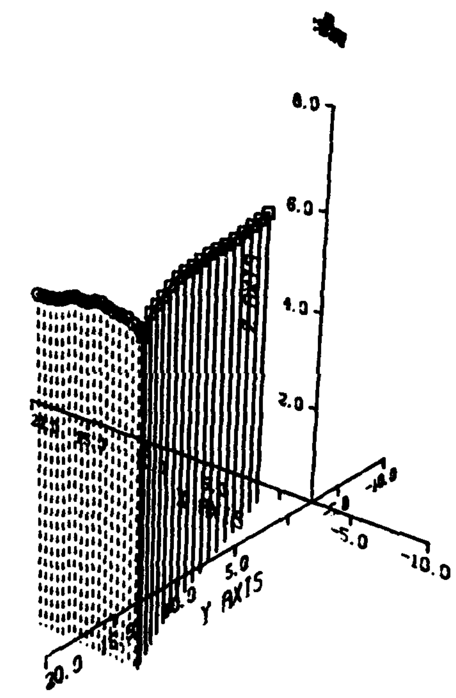


FIGURE B-7 Horizontal Jink W/3.75 Sec Period and Reversal

MISSILE VS TGT TRAJECTORIES(3D)



Miss Distance 45.3 ft

FIGURE B-8 Vertical Jink W/2.1 Sec Period

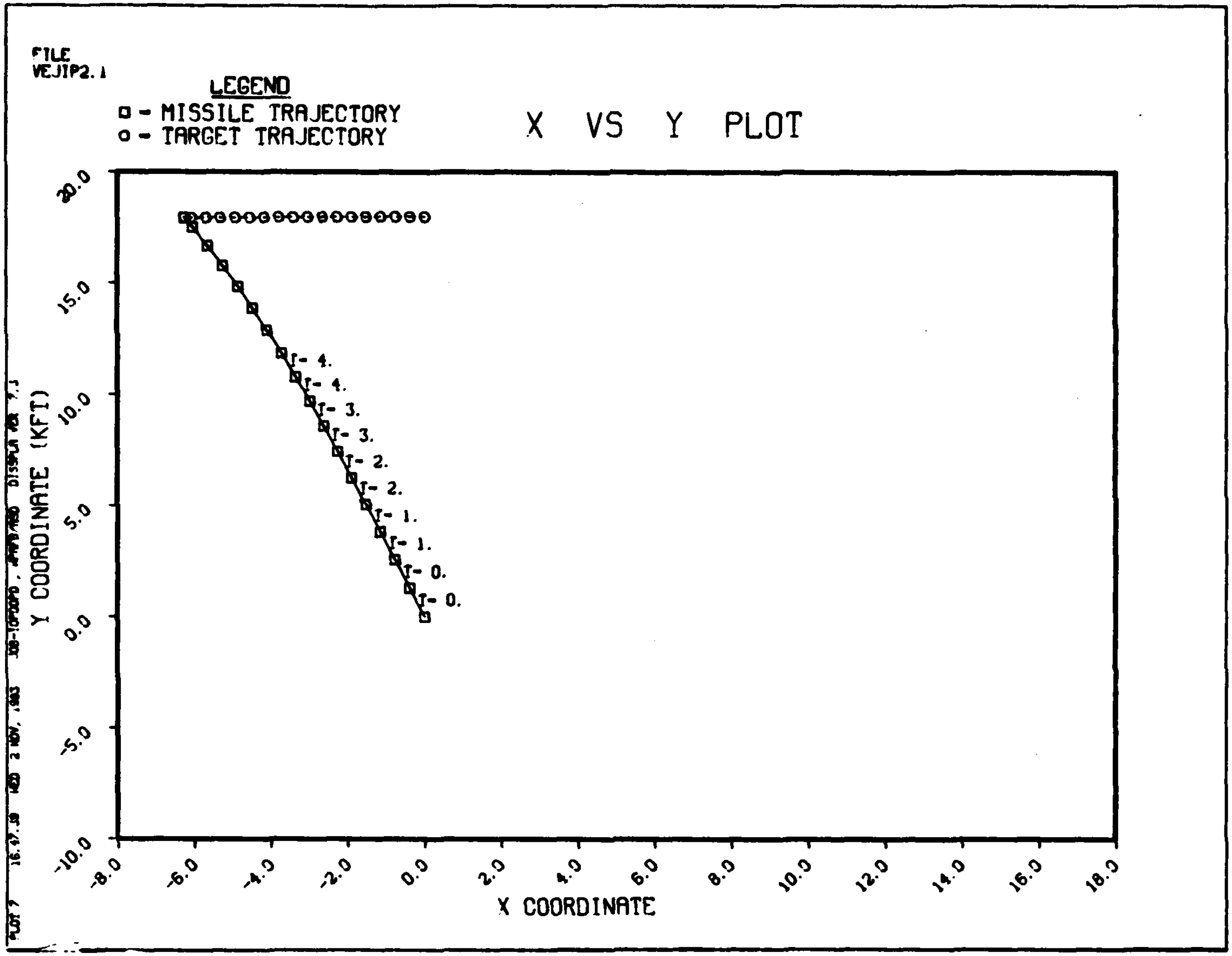


FIGURE B-9 Vertical Jink W/2.1 Sec Period

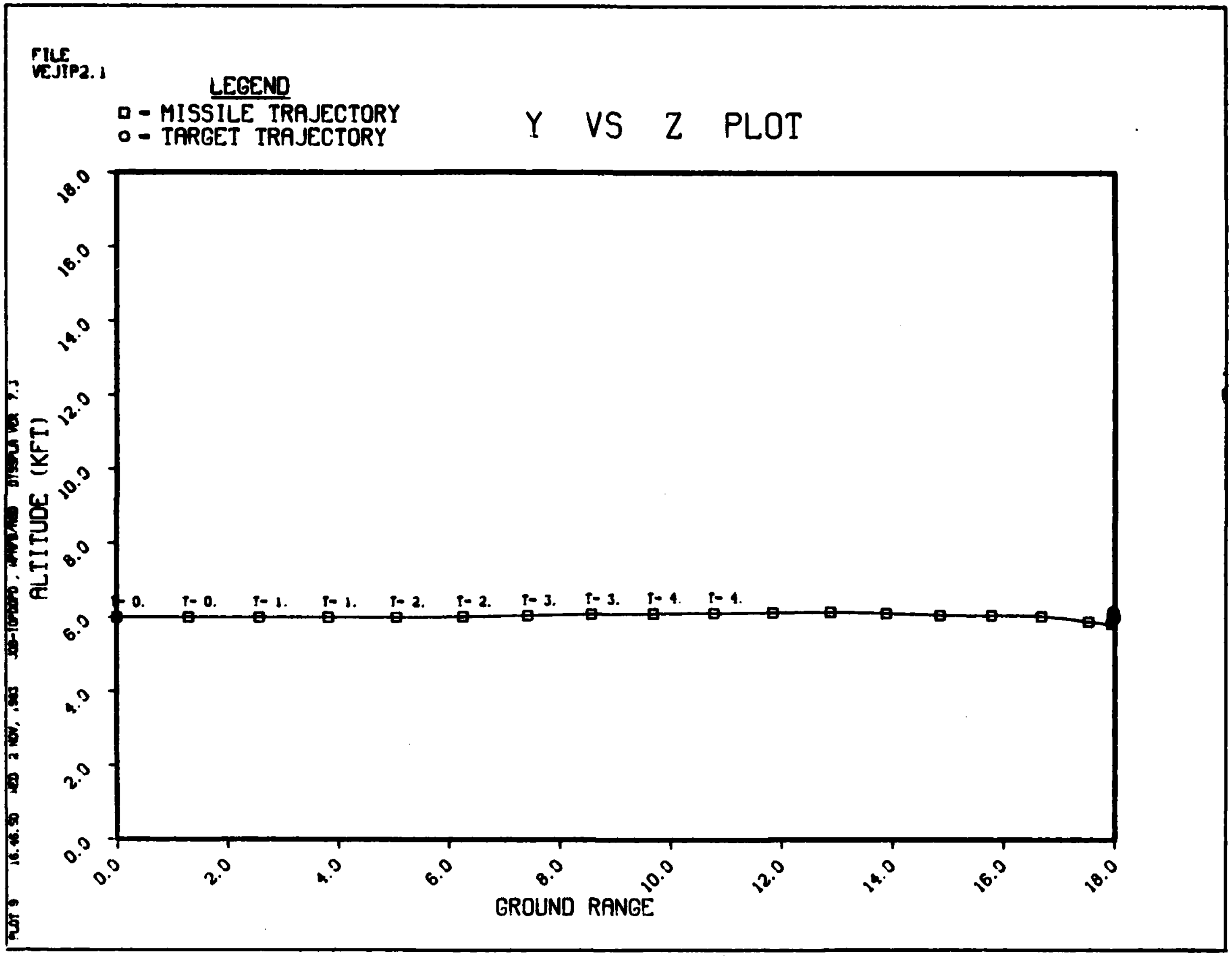


FIGURE B-10 Vertical Jink W/2.1 Sec Period

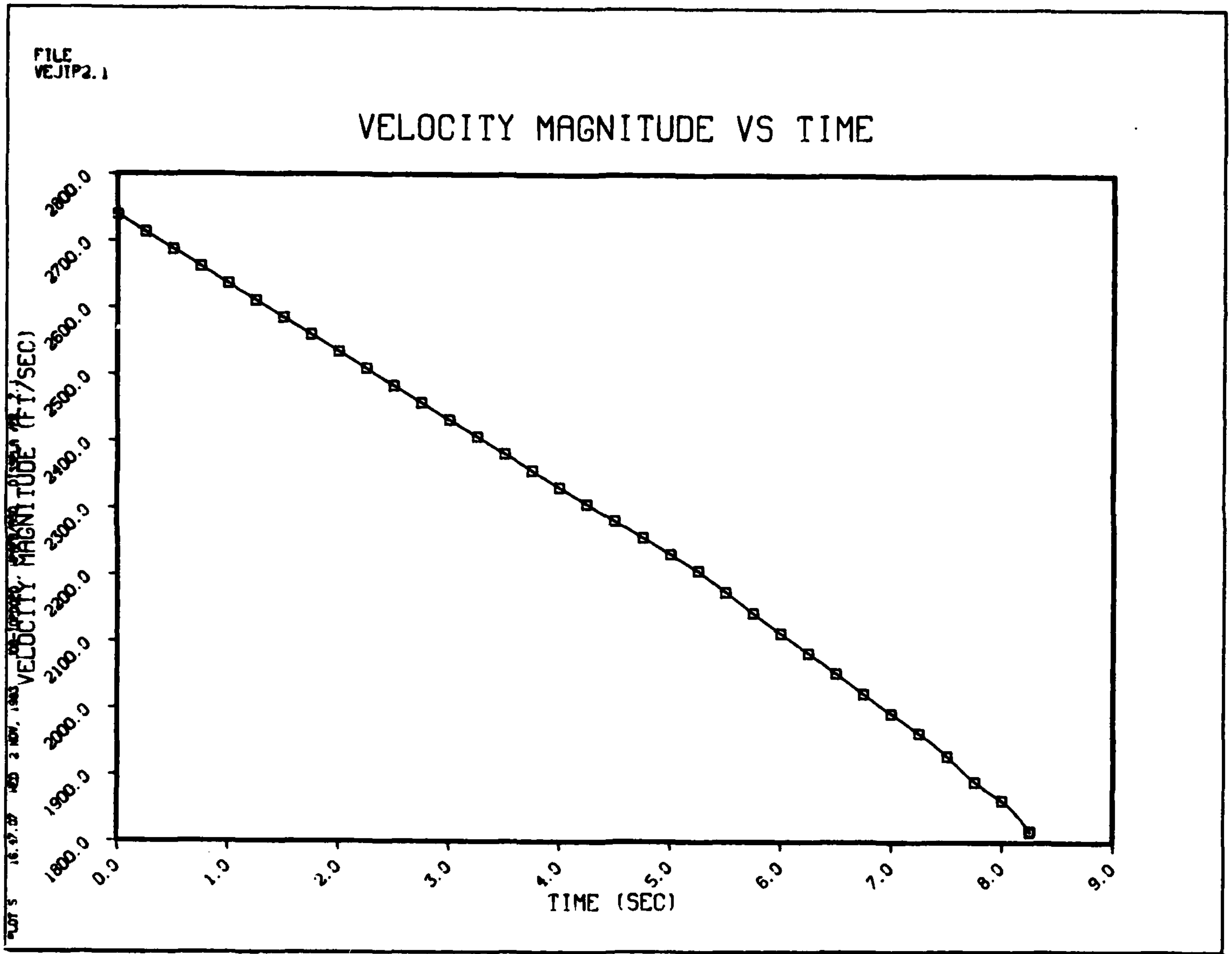


FIGURE B-11 Vertical Jink W/2.1 Sec Period

MISSILE VS TGT TRAJECTORIES(3D)

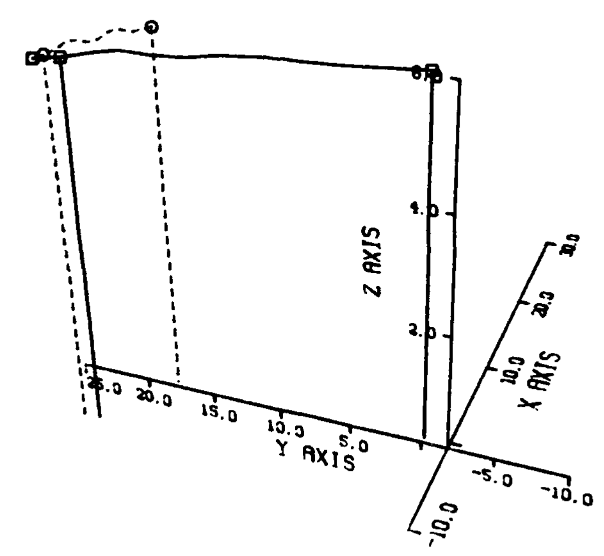


FIGURE B-12 Barrel Roll 90 Deg/Sec Roll Rate

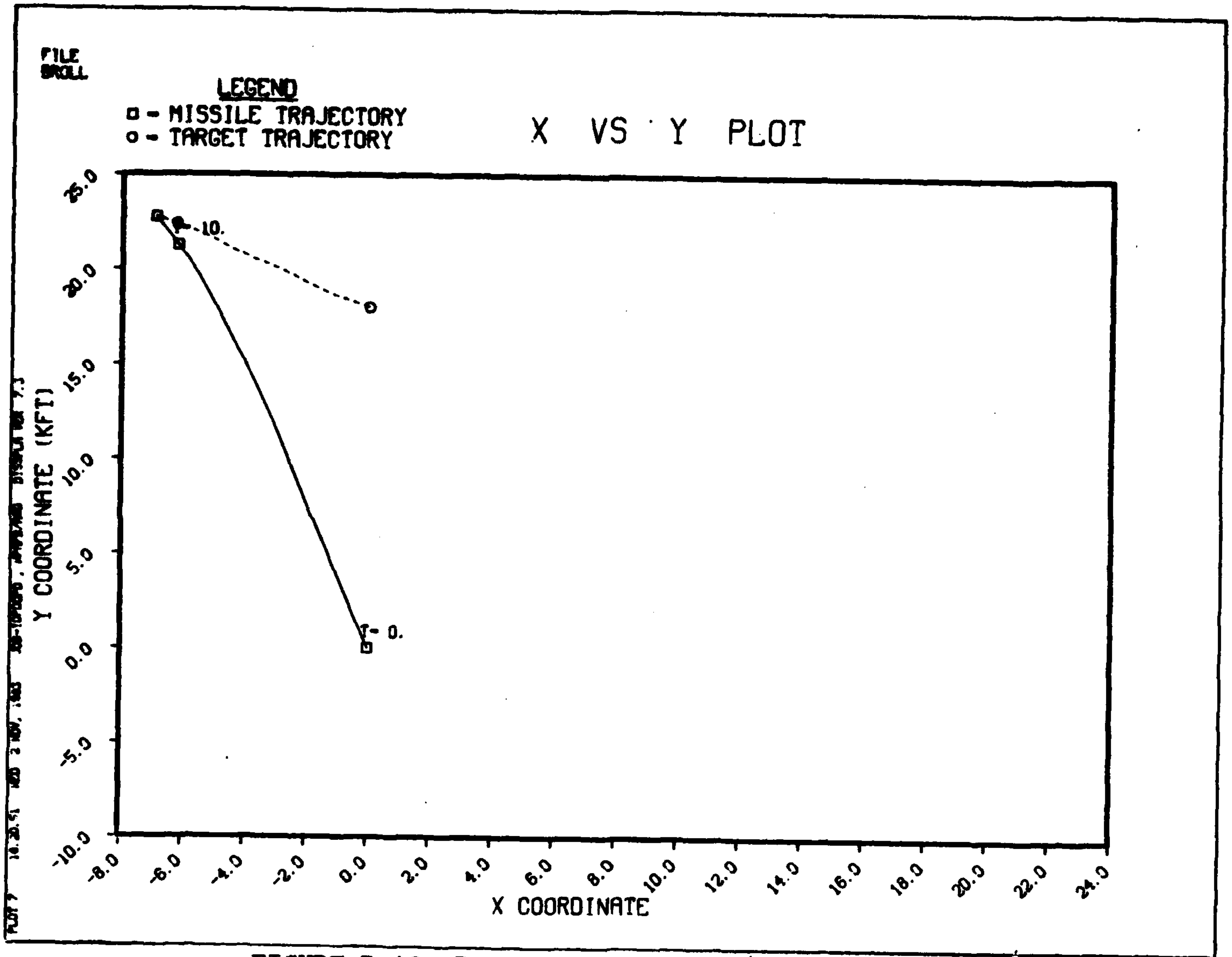


FIGURE B-13 Barrel Roll 90 Deg/Sec Roll Rate

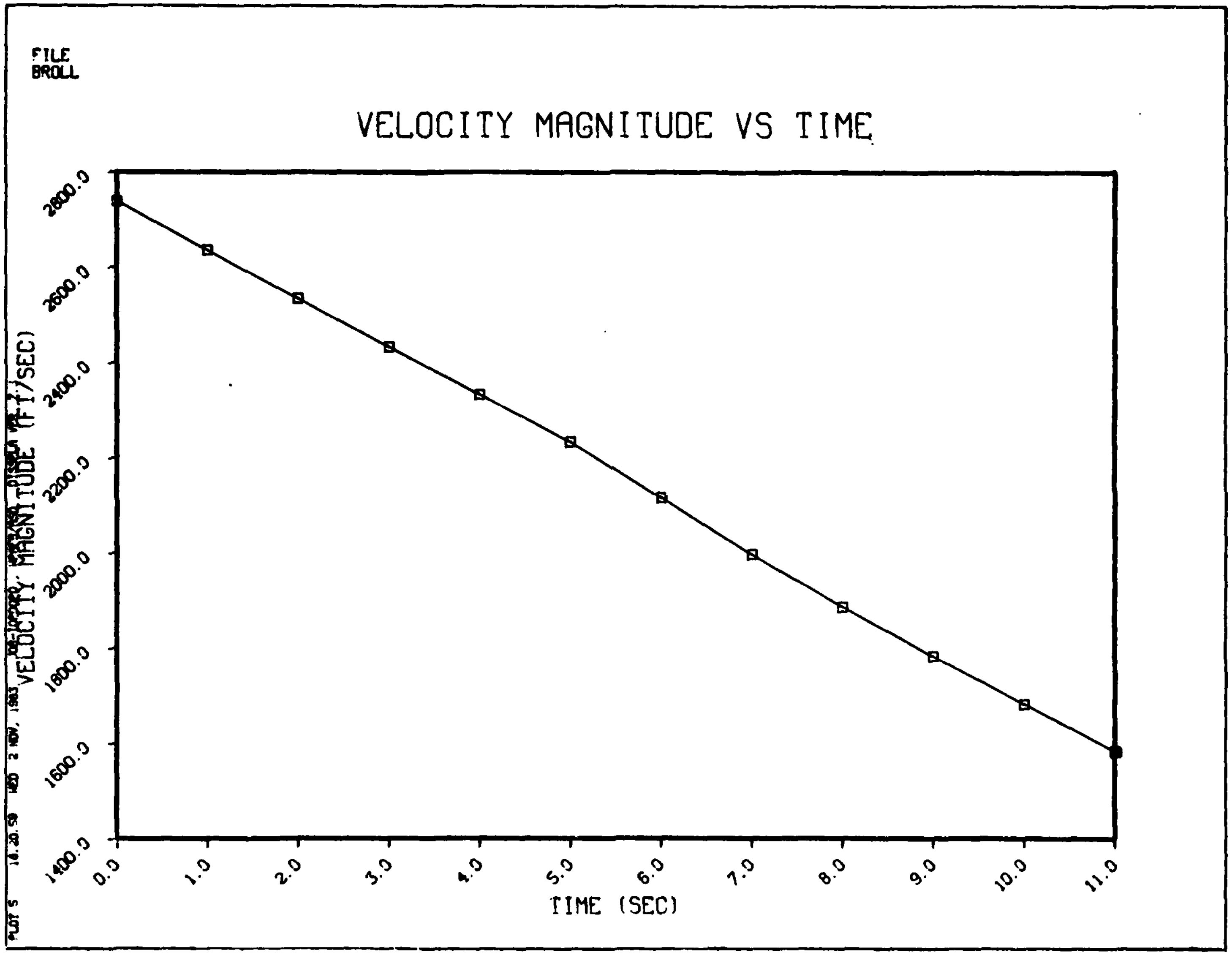


FIGURE B-14 Barrel Roll 90 Deg/Sec Roll Rate

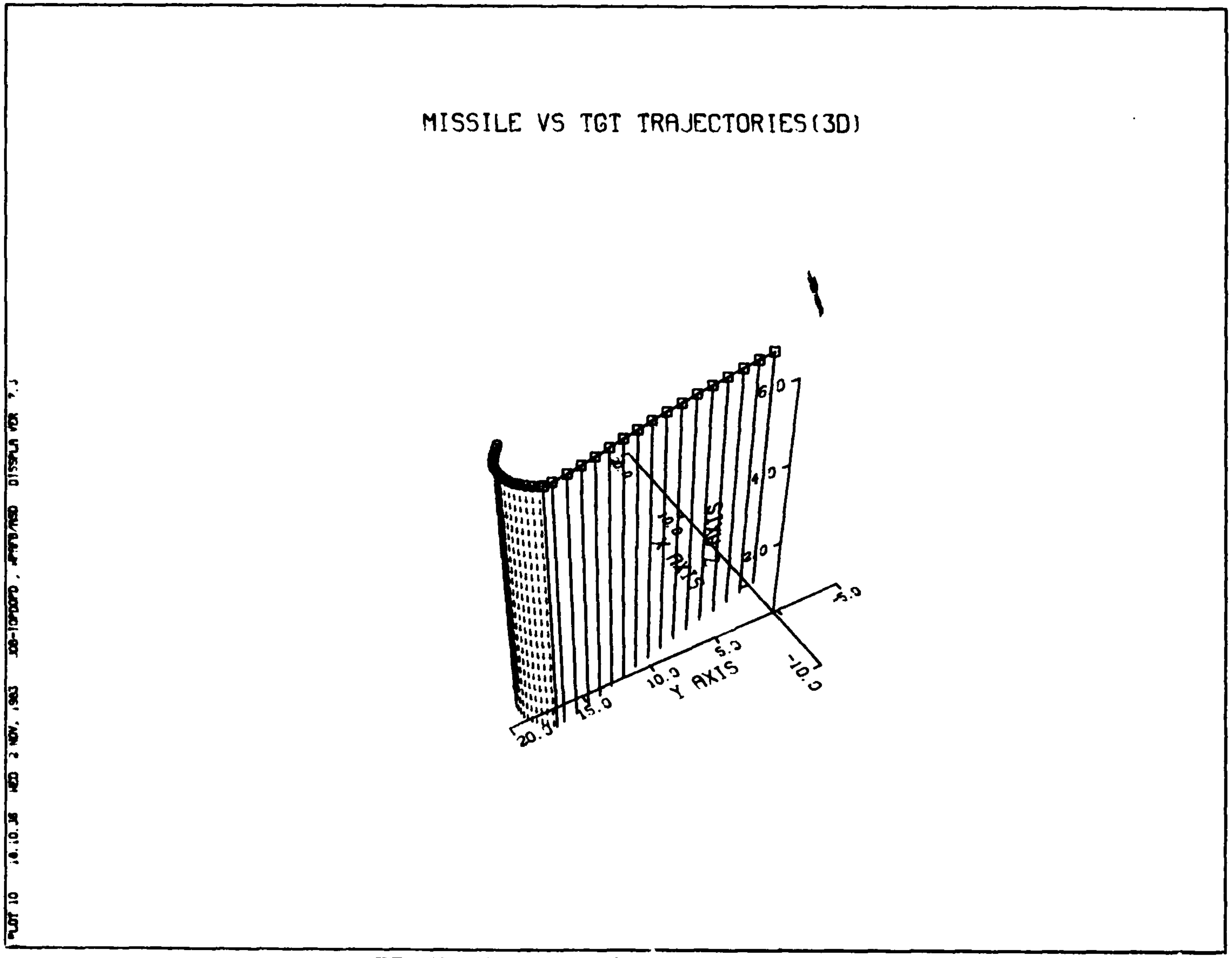


FIGURE B-15 Horizontal Maximum G Turn

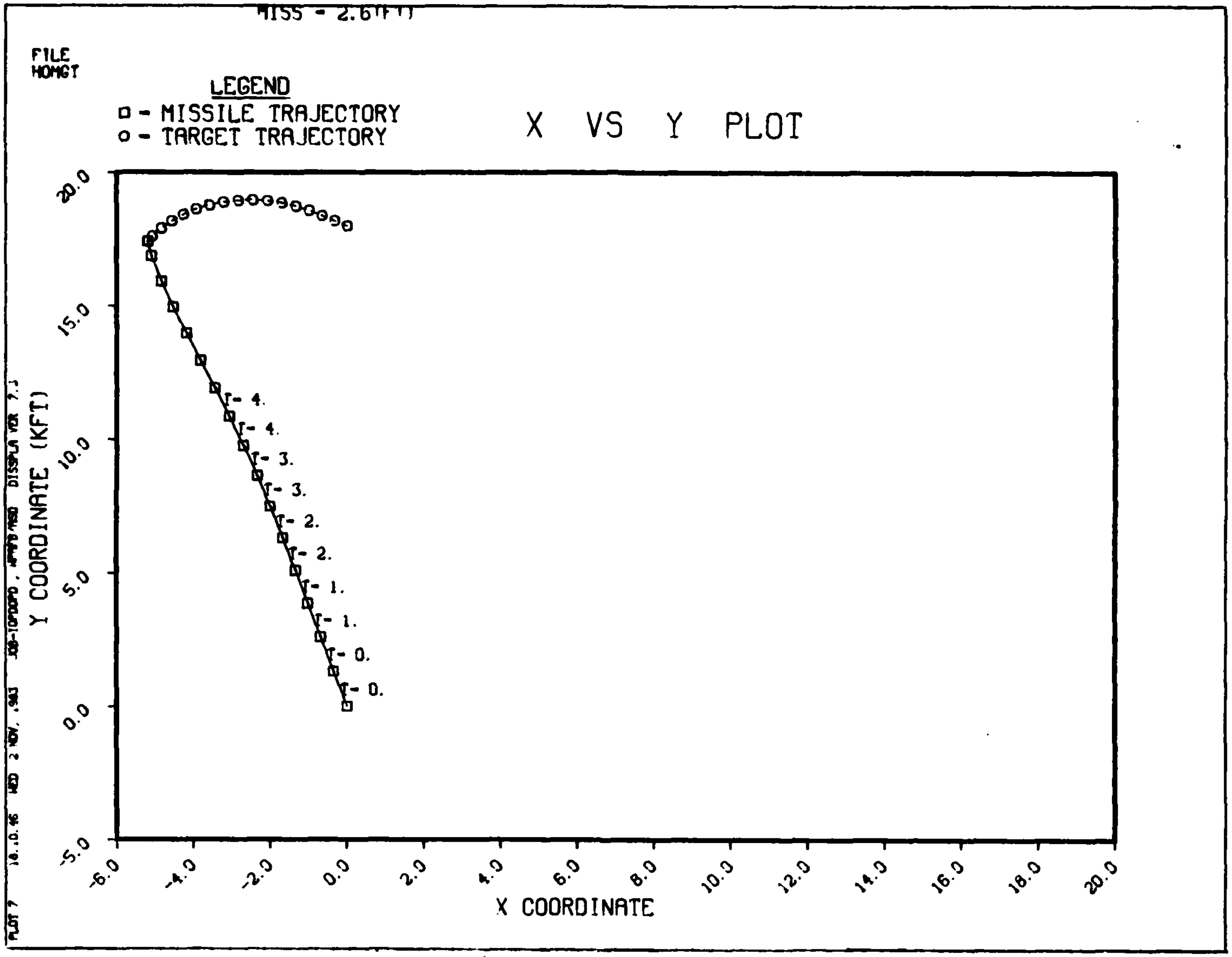


FIGURE B-16 Horizontal Maximum G Turn

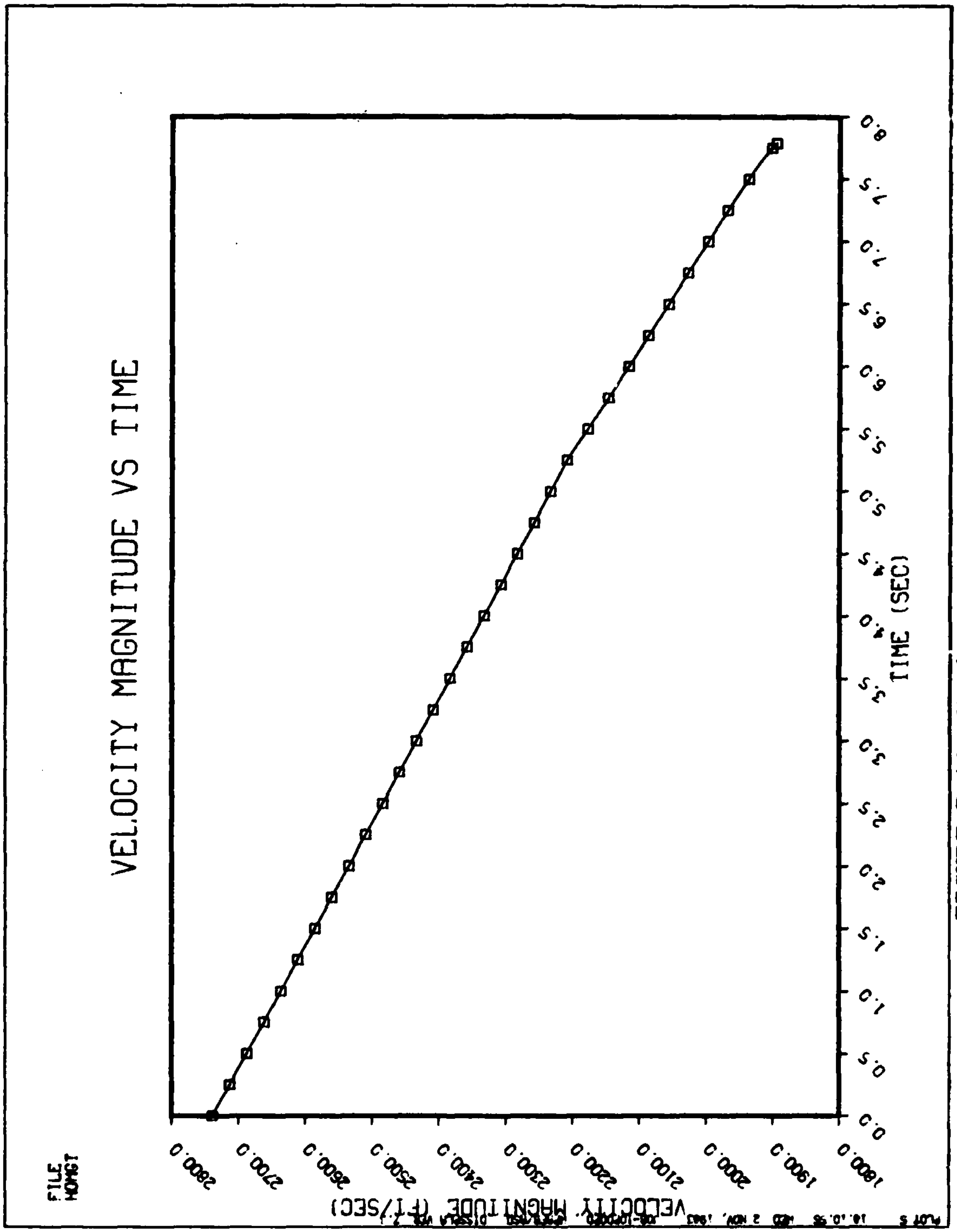


FIGURE B-17 Horizontal Maximum G Turn

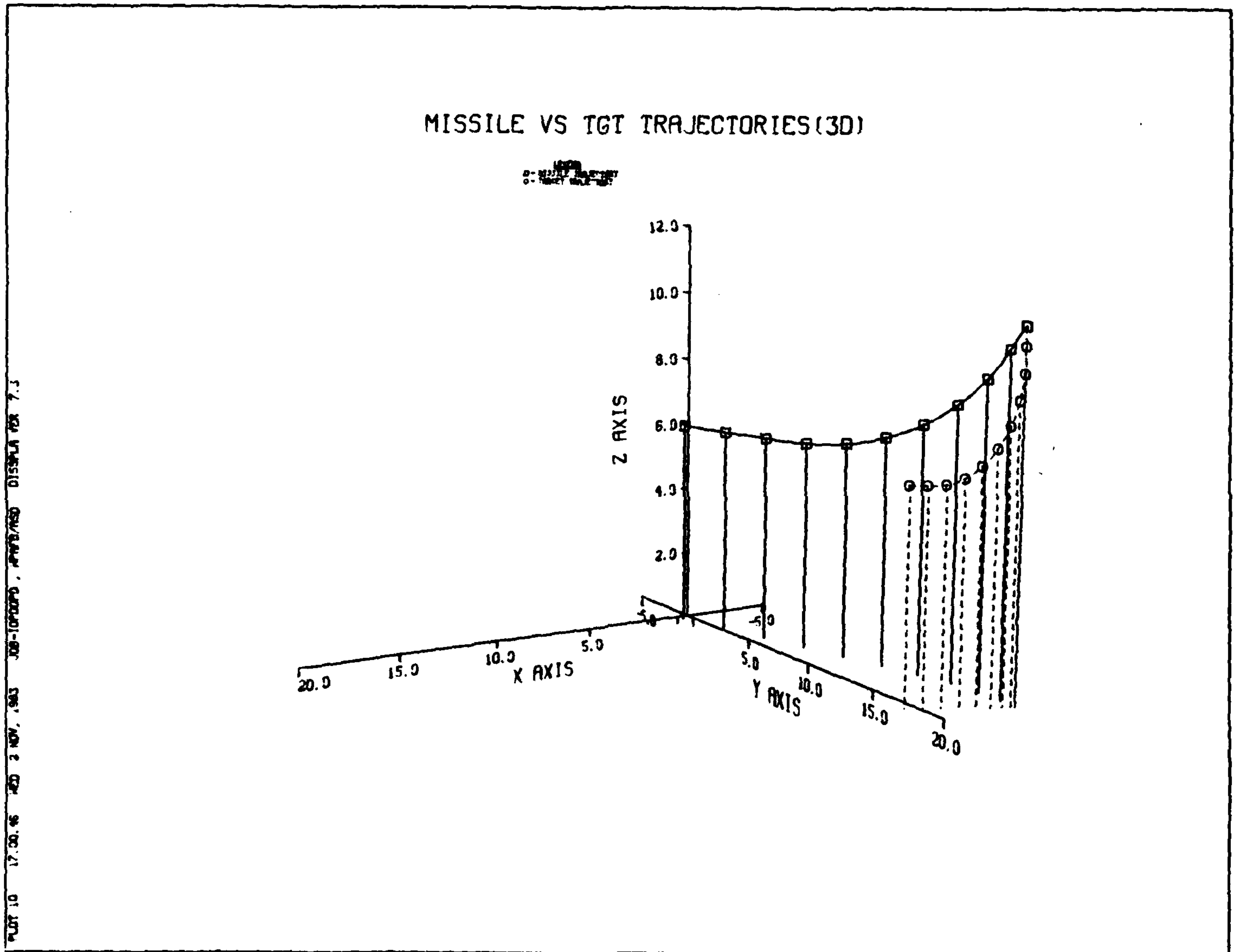


FIGURE B-18 Vertical Maximum G Turn

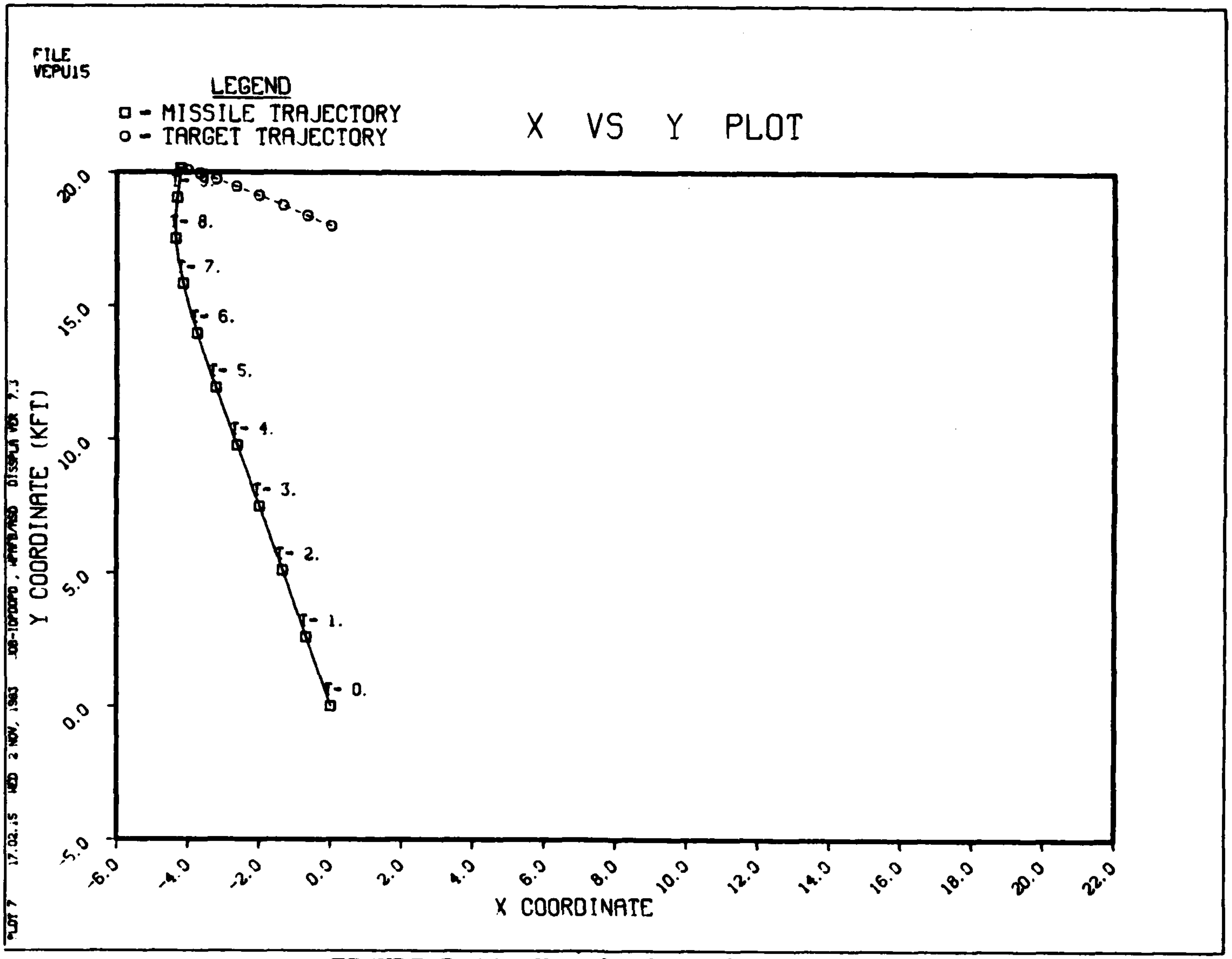


FIGURE B-19 Vertical Maximum G Turn

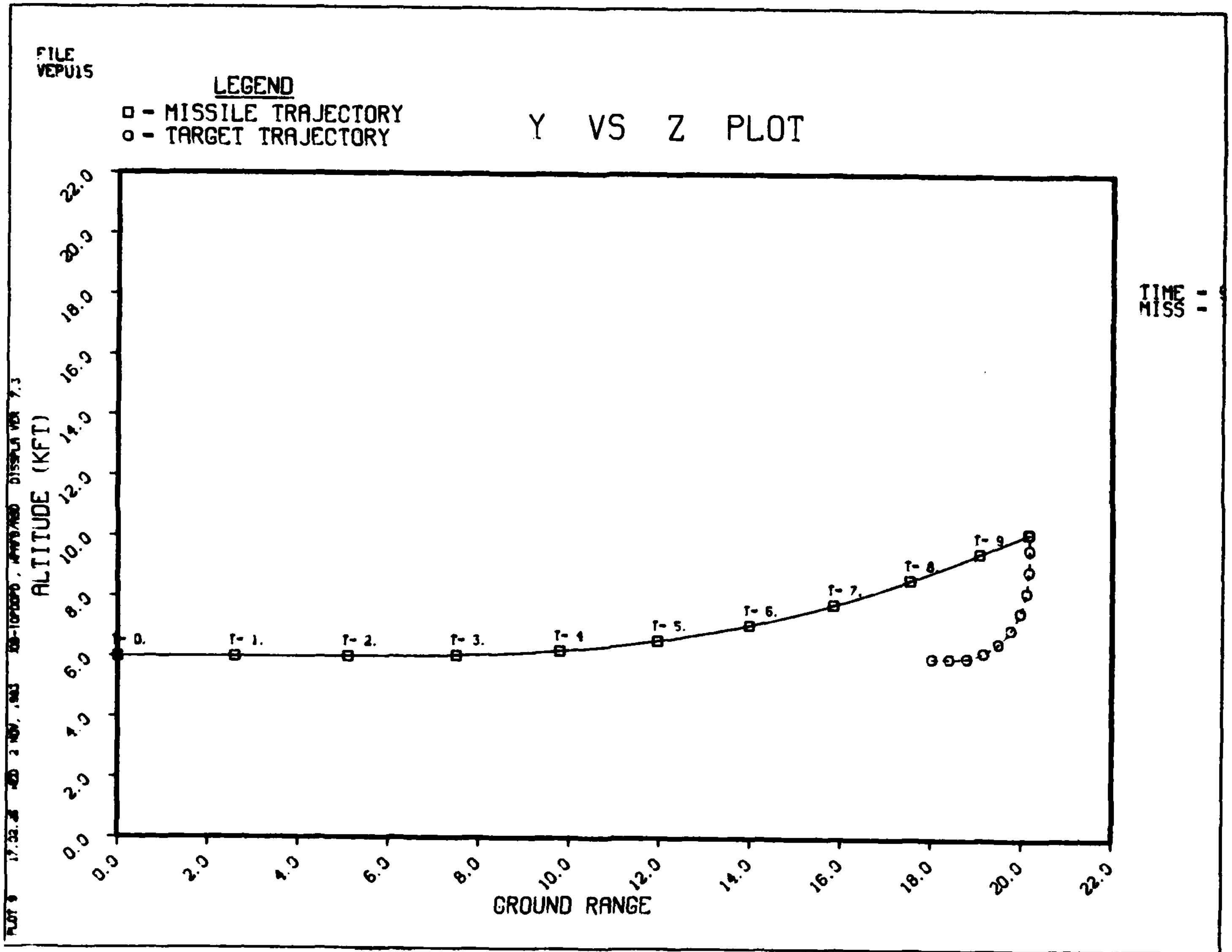


FIGURE B-20 Vertical Maximum G Turn

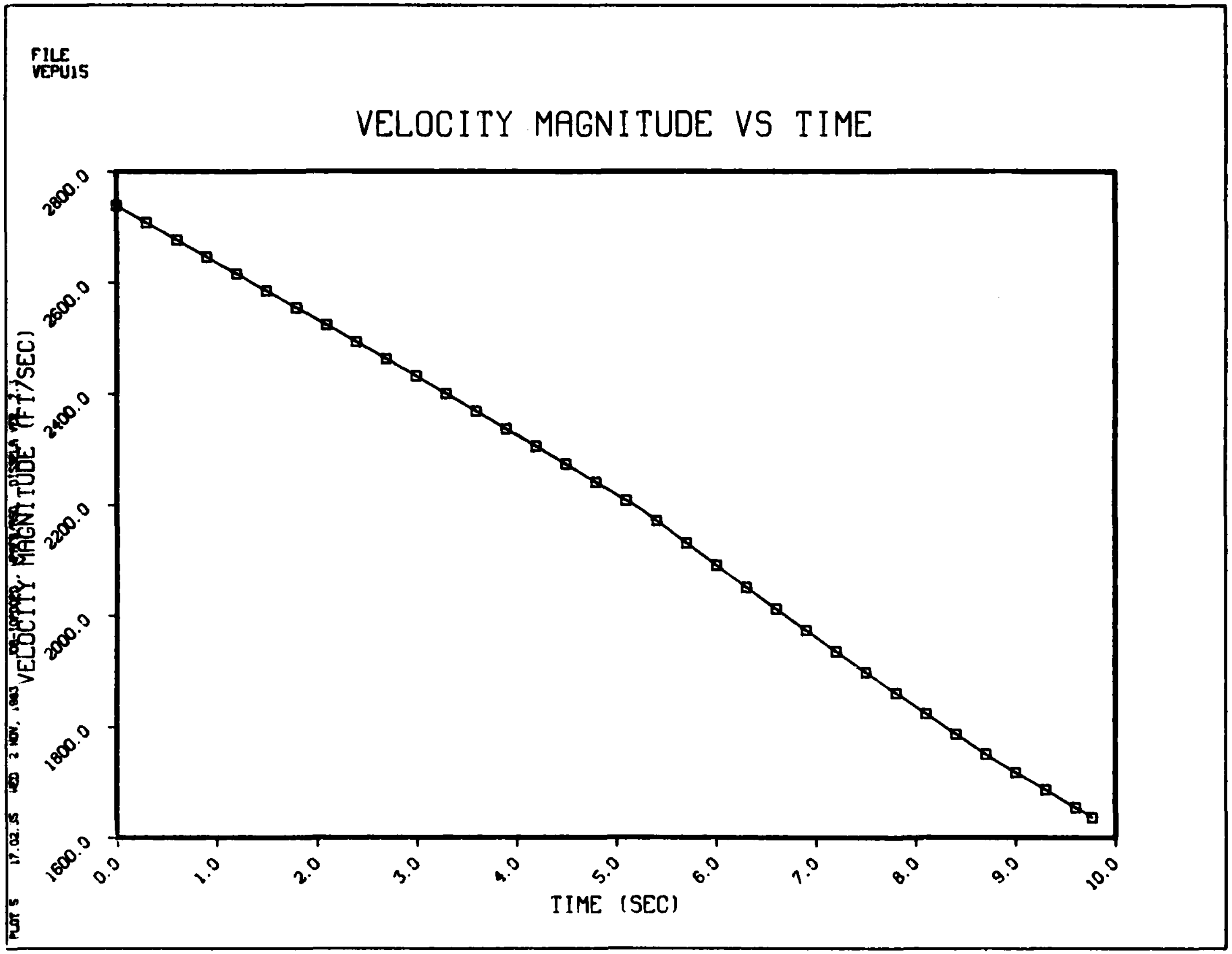


FIGURE B-21 Vertical Maximum G Turn

APPENDIX C

AIRCRAFT ATTITUDE AND COORDINATE FRAMES

This appendix will give an understanding of the transformations and angles used to define aircraft and missile coordinate frames. These transformations and angles are used to help visualize the relative azimuth and elevation angles for the line-of-sight vector with respect to the aircraft coordinate frame. The pilot uses the relative azimuth (η) and relative elevation (ϵ) to establish the plane normal to the LOS vector in which to perform the jinking maneuver.

The LOS vector, $\bar{R}$, is defined by Equation C.1 where $\bar{r}_t$

$$\bar{R} = \bar{r}_m - \bar{r}_t \tag{C.1}$$

and $\bar{r}_m$ are the target and missile position vectors in the inertial coordinate frame $\hat{X},\hat{Y},\hat{Z}$. Fig C.1. To find the relative azimuth and elevation angles of the LOS vector the vector $\bar{R}$ must be transformed into the aircraft coordinate frame. The aircraft coordinate system is a right, orthogonal system with the unit vectors $\hat{1}_t,\hat{1}_p$ and $\hat{1}_y$. The unit vectors are orientated so that $\hat{1}_t$ is parallel to the aircraft roll axis, $\hat{1}_p$ is out the right wing (pitch axis) and $\hat{1}_y$ is out the bottom of the aircraft (yaw axis) Fig C.2. To transform the LOS vector from the inertial coordinate frame $(\hat{X},\hat{Y},\hat{Z})$ into the aircraft coordinate frame $(\hat{1}_t,\hat{1}_p,\hat{1}_y)$ requires

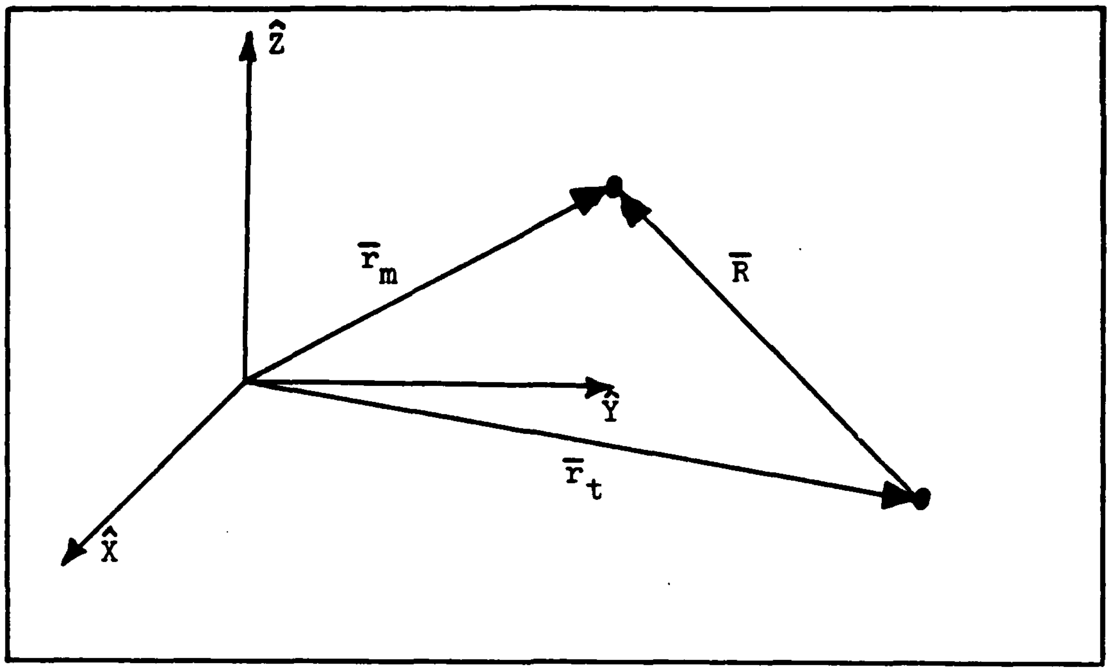


Figure C.1 Inertial Coordinate Frame

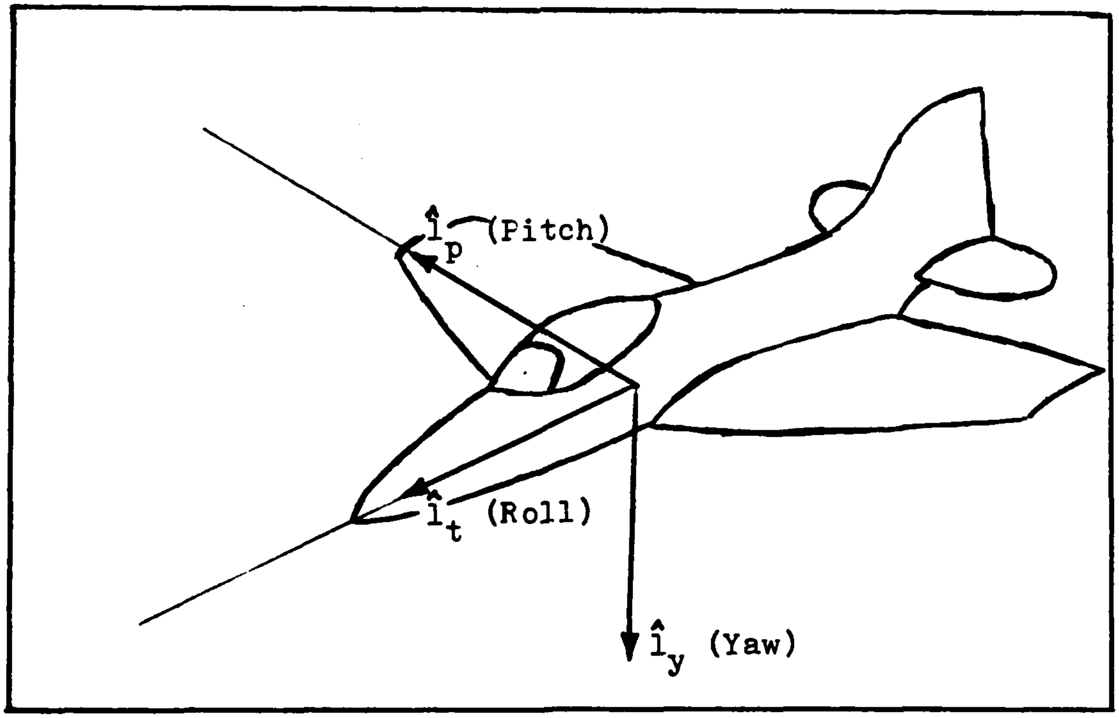


Figure C.2 Aircraft Coordinate Frame

three coordinate transformations.

The first transformation takes a vector from inertial coordinates into the first intermediate coordinate frame $(\hat{i}_v,\hat{i}_a,\hat{i}_d)$. These intermediate unit vectors are orientated with $\hat{i}_v$ along the aircraft velocity vector and i_a parallel to the ground ($\hat{X},\hat{Y}$ plane). The unit vector $\hat{i}_d$ completes the right hand set in the direction of $\hat{i}_v$ cross $\hat{i}_a$. The coordinate transformation requires a rotation of β about the $\hat{Z}$ axis followed by a γ rotation about $\hat{i}_a$ where a positive direction is counterclockwise. Fig C.3. The coordinate transformation is as shown below.

$$\begin{Bmatrix} \hat{i}_v \\ \hat{i}_a \\ \hat{i}_d \end{Bmatrix} = \begin{bmatrix} \cos\beta\cos\gamma & \cos\gamma\sin\beta & \sin\gamma \\ -\sin\beta & \cos\beta & 0 \\ -\sin\gamma\cos\beta & -\sin\gamma\sin\beta & \cos\gamma \end{bmatrix} \begin{Bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{Bmatrix} \quad (C.2)$$

The next coordinate transformation is a rotation about $\hat{i}_v$ through the bank angle ψ_b. This second intermediate coordinate frame is $(\hat{i}_v,\hat{i}_e,\hat{i}_u)$. Fig C.4. The second coordinate transformation is as follows.

$$\begin{Bmatrix} \hat{i}_v \\ \hat{i}_e \\ \hat{i}_u \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_b & \sin\psi_b \\ 0 & -\sin\psi_b & \cos\psi_b \end{bmatrix} \begin{Bmatrix} \hat{i}_v \\ \hat{i}_a \\ \hat{i}_d \end{Bmatrix} \quad (C.3)$$

The final transformation from the second intermediate frame $(\hat{i}_v,\hat{i}_e,\hat{i}_u)$ to the aircraft frame $(\hat{i}_t,\hat{i}_p,\hat{i}_y)$ requires two rotations. The first is a 180 degree rotation about $\hat{i}_v$

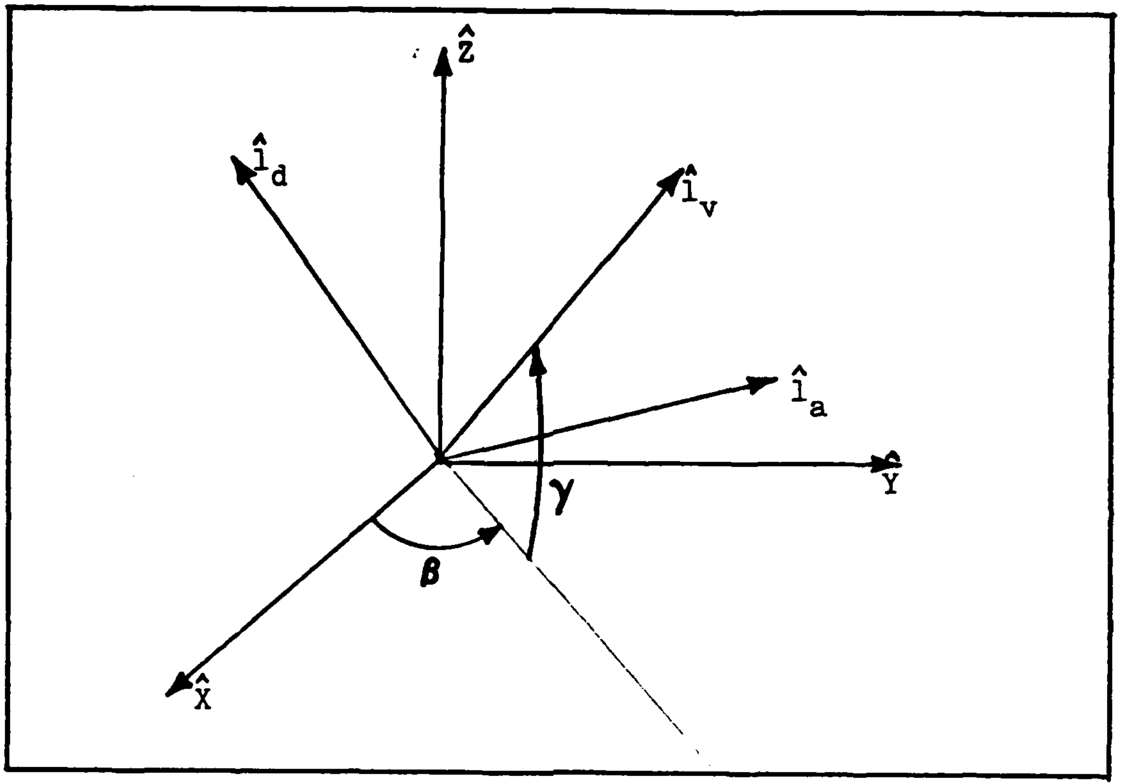


Figure C.3 Rotations from Inertial to 1st Intermediate Coordinate Frames

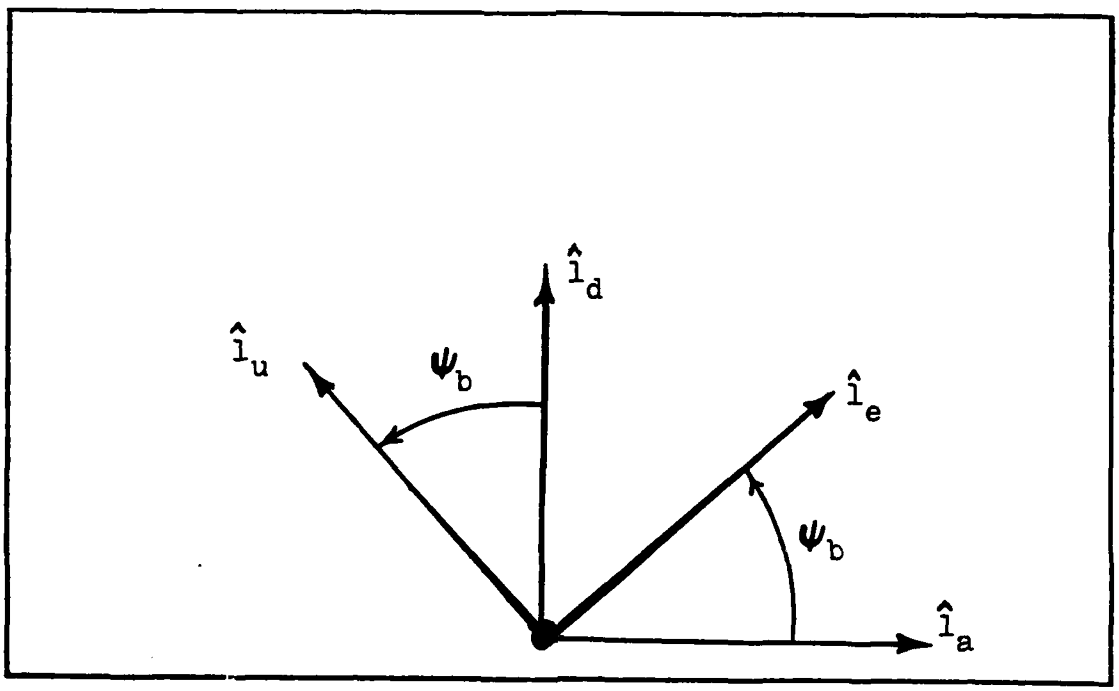


Figure C.4 Bank Angle Rotation to 2nd Intermediate Coordinate Frame

so that $\hat{i}'_e$ points out the right wing. Fig C.5. the second rotation is through the angle of attack, α, about $\hat{i}'_e$. Fig C.6. Thus the final coordinate transformation is seen below.

$$\begin{Bmatrix} \hat{i}_t \\ \hat{i}_p \\ \hat{i}_y \end{Bmatrix} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & -1 & 0 \\ \sin\alpha & 0 & -\cos\alpha \end{bmatrix} \begin{Bmatrix} \hat{i}_v \\ \hat{i}_e \\ \hat{i}_u \end{Bmatrix} \qquad \text{(C.4)}$$

Using all three coordinate transformations the LOS vector can be transformed into the aircraft coordinate frame. The relative azimuth, η, and relative elevation, ϵ, are shown in Fig C.7. Using the LOS unit vector, $\hat{i}_r$, the angles η and ϵ can be calculated with Equations C.5 and C.6.

$$\epsilon = \arccos(\hat{i}_r \cdot \hat{i}_y) - 90^\circ = \arcsin(\hat{i}_r \cdot -\hat{i}_y) \qquad \text{(C.5)}$$

$$\eta = \arctan\left(\frac{\hat{i}_r \cdot \hat{i}_p}{\hat{i}_r \cdot \hat{i}_t}\right) \qquad \text{(C.6)}$$

The computer simulation TACTICS IV uses coordinate transformations very similar to these to compute η and ϵ. (Ref 8:89-91)

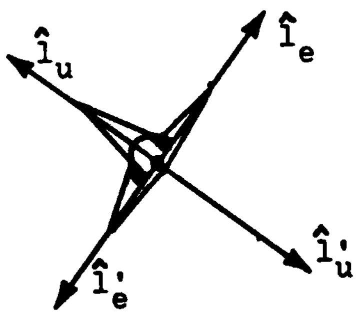


Figure C.5 180 Degree Rotation

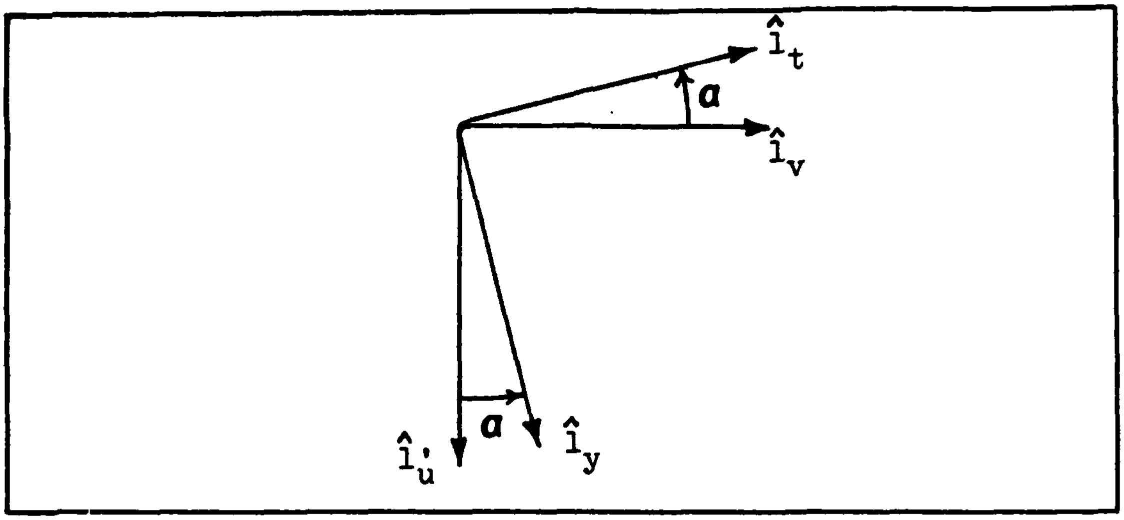


Figure C.6 Angle of Attack Rotation to Aircraft Coordinate Frame

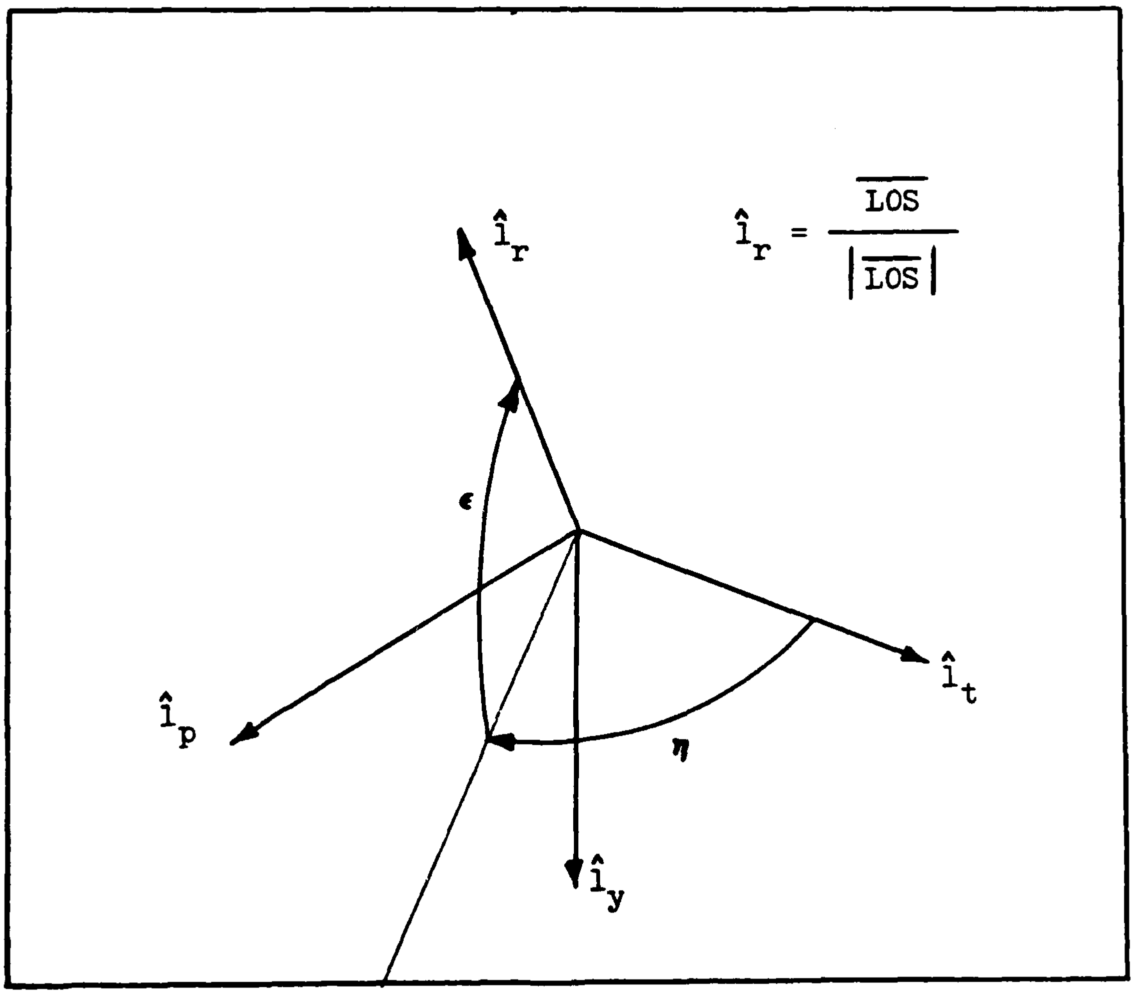


Figure C.7 Relative Azimuth and Elevation

Appendix D

CHANGES TO TACTICS IV

TACTICS IV provided several target maneuvers which were a very good basis for testing target maneuvers against a PN guided missile. After a prelimimary investigation of target maneuvers which might give the largest miss distance, the need to improve on already existing maneuvers in TACTICS IV became apparent. A jinking maneuver in a plane other than the horizontal was needed. The ability to make so e type of maneuver change after initiating the initial move was also a desired change to the original TACTICS IV program.

To provide for a three dimensional jinking maneuver, Subroutine Jink was modified. Subroutine Jink had used the planar turning Subroutine Turn 2D as a basic target maneuver. The change to Subroutine Jink was to have Subroutine Turn 3D called to provide the basic target maneuvering. To allow a maneuver change after the initial target maneuver began, a series of program steps were added to Subroutine Turn 3D. This change to Turn 3D permits a bank angle change to occur at a specified time-to-go until impact. Input data values 81 through 83 were used. Data 81 is used as a flag and is initialized to zero in Subroutine Incond. Data 83 is the number of degrees the bank angle is changed and Data 82 is the TGO used to make the bank change. On the following pages Subroutine Jink and Turn 3D are listed

with bold black lines in the left margin next to the changed or added program lines.

```
      SUBROUTINE JINK
      ---------
      COMMON  STATEMENTS
      ---------
      IF(ACTNO(3).EQ.14.0) GO TO 10
      T1=TIME
      OMEGAX=TWOPI/PERIOD
      SIGNO=SIGN(1.0,ACCTGT)
   10 CONTINUE
      SINEX=SIN(OMEGAX*(TIME-T1))*SIGNO
      ACCTGT =ABS(ACCTGT)*SIGN(1.0,SINEX)
         CALL TURN3D(3)
      DO 50 J=1,2
   50 ACTION(3,J)=AJINK(J)
      RETURN
      END


      SUBROUTINE TURN3D(I)
      ---------
      COMMON STATEMENTS
      ---------
      IF(ACTNO(I).EQ.14.0) GO TO 300
C     INITIALIZE INTEGRATION AT START OF MANEUVER
C
      ZVAR(1)=R(3,1)
      ZVAR(2)=R(3,2)
      ZVAR(3)=R(3,3)
      ZVAR(4)=V(3,1)
      ZVAR(5)=V(3,2)
      ZVAR(6)=V(3,3)
      XT=TIME
C***INITIALIZE LAG OR AUTOPILOT ROUTINES
      CALL LAG(I)
      ROLL(I)=TGTROL*RAD
  300 CONTINUE
      ESTGO=ABS(RREL(3,4)/RDOT(3))
      IF(DATA(81).EQ.1.0) GO TO 19
      IF(ESTGO.GE.DATA(82)) GO TO 19
      DATA(81)=1.0
      IF(TGTROL.LT.0.0) ROLL(I)=ROLL(I)+DATA(83)*RAD
      IF(TGTROL.GT.0.0) ROLL(I)=ROLL(I)-DATA(83)*RAD
   19 CONTINUE
      GFORCE(I)=ACCTGT
      ---------
      THE REMAINDER OF TURN3D IS UNCHANGED
```

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VITA

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Proportional navigation is a guidance law used on many missiles today. Closed loop missile evasion maneuvers for fighters flying against proportional navigation missiles have been investigated, but they all require that the fighter have relative state information that is currently unavailable. An open loop missile evasion algorithm is needed today to allow pilots to best maneuver their aircraft against PN guided missiles to improve the chances of survival.

A preliminary investigation of fighter maneuvers revealed the strengths and weakness of particular maneuvers. Maximum g turns and barrel rolls were expected to shwo little increase in miss distance over a non-maneuvering target. A switching/jinking maneuver coupled with a last second bank reversal was thought to be the best evasive maneuver.

The computer simulation TACTICS IV was used to simulate fighter/missile engagements. From those simulations the miss distance was calculated and used to determine the best fighter maneuver. As expected maximum g turns in any direction and barrel rolls proved to be the worst evasive maneuvers. A rapid jinking maneuver that times the last reversal to occur with about one second until impact and is done in a plane perpendicular to the line-of-sight vector showed the largest increase in miss distance.

The open loop evasion algorithm for a PN missile is simple and centers around the missile being seen by the pilot. If a launch is detected but the missile is not in view, the pilot should jink as quickly as possible and in any direction. If the pilot sees the missile he should jink in a plane perpendicular to the line-of-sight vector and time the last switch to occur about one second before impact. If the missile is already one second from impact when first seen a maximum g turn perpendicular to the line-of-sight vector should be done immediately.